

QCD Puzzles, Predictions and Prognosis:

What can ν do for you?

Fred Olness

SMU

Conspirators: NuSOnG Collaboration

T. Adams, P. Batra, L. Bugel, L. Camilleri, J.M. Conrad, A. de Gouvea, P.H. Fisher,
J.A. Formaggio, J. Jenkins, G. Karagiorgi, T.R. Kobilarcik, S. Kopp, G. Kyle, W.A.
Loinaz, D.A. Mason, R. Milner, R. Moore, J.G. Morfin, M. Nakamura, D. Naples, P.
Nienaber, F.I. Olness, J.F. Owens, S.F. Pate, A. Pronin, W.G. Seligman, M.H.
Shaevitz, H. Schellman, I. Schienbein, M.J. Syphers, T.M.P. Tait, T. Takeuchi, C.Y.
Tan, R.G. Van de Water, R.K. Yamamoto, J.Y. Yu

Fermi
9 October 2009

LHC to start up in November 2009



Need a physics program that will co-exist with LHC

Example: Tevatron & LEP -- vibrant complementary physics programs

Neutrinos: They mix, have mass, and the ν -CKM is not diagonal
The “original” physics beyond the Standard Model (*by some metrics*)

Neutrinos are an ideal complementary program to go with LHC



1-3 October 2009

Plans for super-beams in Japan

1. J-PARC Accelerator and Neutrino Beam Facility

• J-PARC is a multi-purpose particle accelerator facility located in Japan.
 • It utilizes the existing J-PARC Neutrino Beam for the Daya Bay Experiment.

**EUROPEAN STRATEGY
FOR FUTURE NEUTRINO PHYSICS**

1-3 October 2009 | Main Auditorium

Plans for Super Beams in Europe

Marcos DRACOS
IPHC-IN2P3/CNRS Strasbourg

Superbeams
Beta beams
Neutrino Decay

PS2 / SPL

Neutrino Astrophysics

Neutrino Mass

Neutrino Oscillations

Detector Development

M. Dracos

Plans for superbeams in US

Young-Kee Kim
Fermilab / Univ. of Chicago

October 1-3, 2009

European Strategy for Future Neutrino Physics

Workshop on Applications of High Intensity Proton Accelerators

October 19-21, 2009
Fermi National Accelerator Laboratory, Batavia, IL, USA

Welcome to the Workshop on Applications of High Intensity Proton Accelerators home page



4th Workshop on Physics

with a high intensity proton source, November 9-10 (Monday-Tuesday), 2009

[Fermilab Home](#) | [Fermilab at Work](#) | [Fermilab Directorate](#)

[Home](#)

[Registration](#)

[Registrants List](#)

[Scientific Program](#)

[Workshop Organizers](#)

Workshop Goal:

- Inform the community
 - recent developments on intensity frontier experimental programs at Fermilab
 - evolution of Project X accelerator design
 - physics opportunities with Project X ([draft document](#))
- Produce Project X White Paper



NuSONG Collaboration

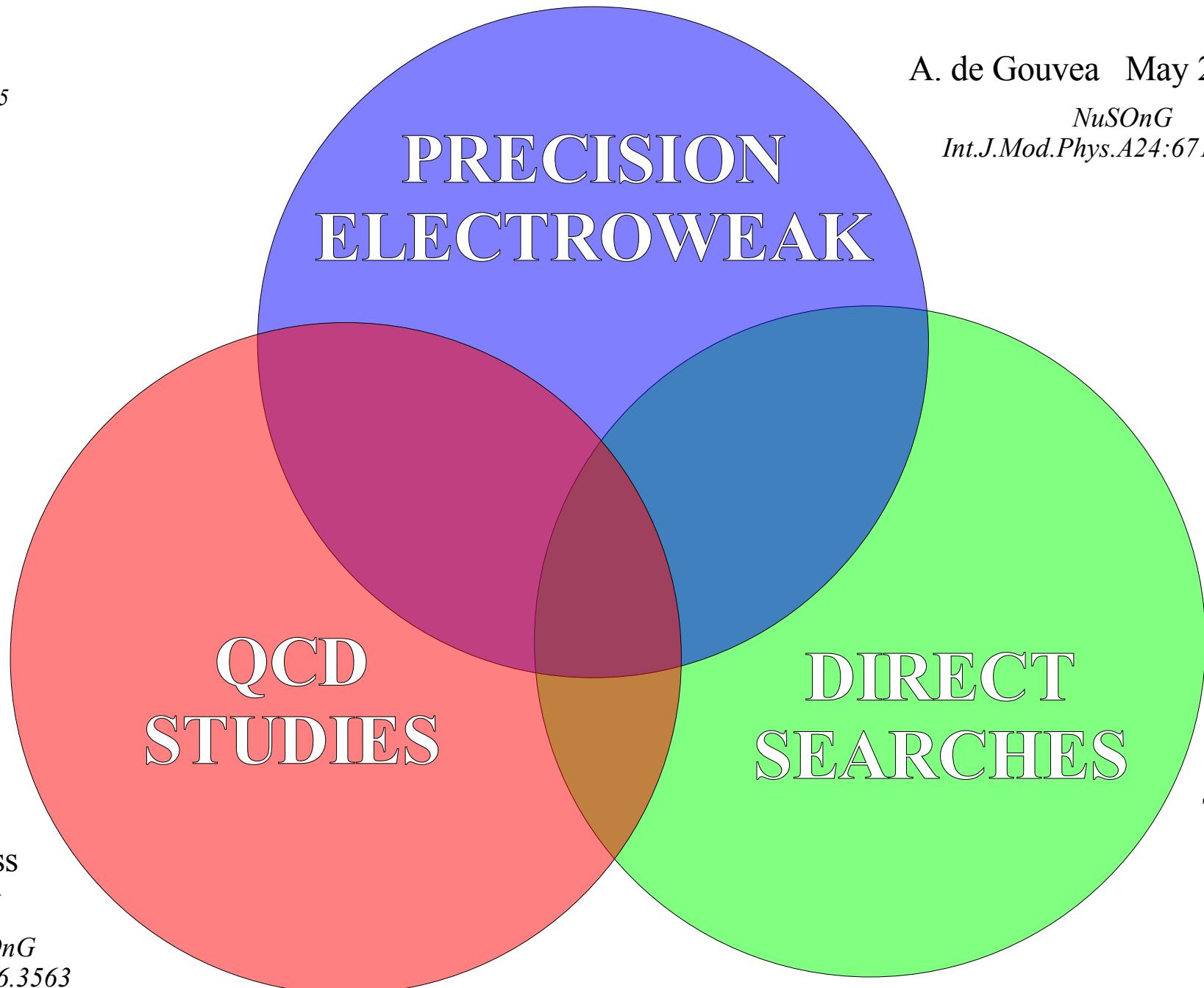
NU'S On Glass

What can we do with a
Hi Energy
Hi Intensity
 ν beam?

NuSONG Collaboration: T. Adams, P. Batra, L. Bugel, L. Camilleri, J.M. Conrad, A. de Gouvea, P.H. Fisher, J.A. Formaggio, J. Jenkins, G. Karagiorgi, T.R. Kobilarcik, S. Kopp, G. Kyle, W.A. Loinaz, D.A. Mason, R. Milner, R. Moore, J.G. Morfin, M. Nakamura, D. Naples, P. Nienaber, F.I Olness, J.F. Owens, S.F. Pate, A. Pronin, W.G. Seligman, M.H. Shaevitz, H. Schellman, I. Schienbein, M.J. Syphers, T.M.P. Tait, T. Takeuchi, C.Y. Tan, R.G. Van de Water, R.K. Yamamoto, J.Y. Yu



... a la P5



A. de Gouvea May 2008

NuSOnG

Int.J.Mod.Phys.A24:671, 2009

F. Olness
Today

NuSOnG
arXiv:0906.3563

Tevatron
LHC



These measurements interdependent and part of the foundation we use to calibrate the search for “new physics”

- Direct Searches at Tevatron & LHC
 - Higgs Boson
 - SUSY *and beyond*
- Precision ElectroWeak
 - Extended W'/Z' and Higgs
 - $\text{Sin}\theta_W$
 - R-violating SUSY Models
 - various lepto-quark models
- QCD Studies
 - PDFs Extraction
 - Isospin Symmetry Violation
 - s(x) & c(x) distributions
 - Impact on W/Z Benchmarks @ LHC

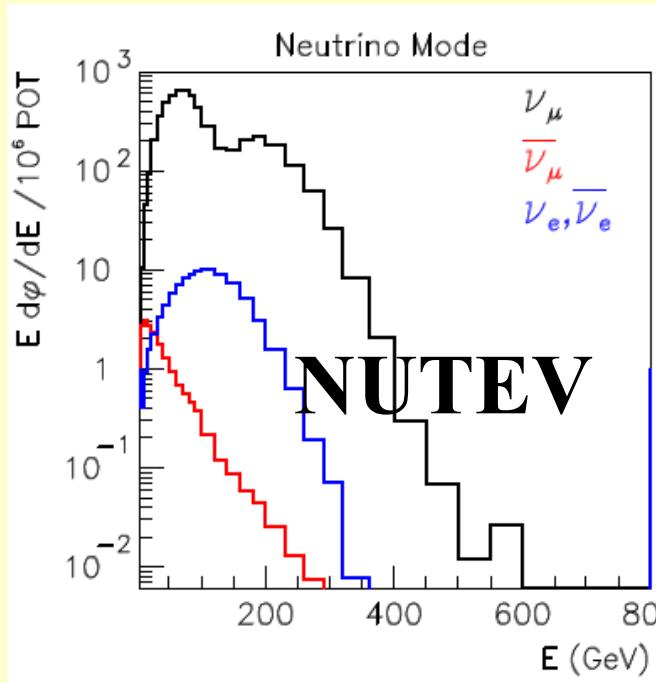
NuSONG

The Parameters

The Detector

Hi Statistics

Hi Energy



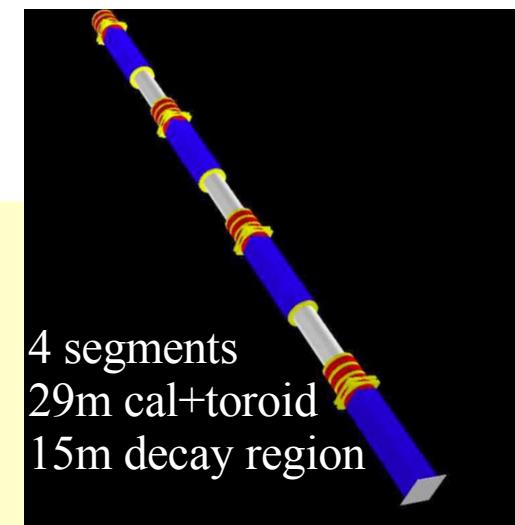
High energy,
very pure beam
($\times 20$ POT)

Fine-grained,
massive detector
($\times 6$ mass) 3 kTon fiducial volume

1.5E20 POT in ν ,
0.5E20 POT in $\bar{\nu}$
 $x = [0.0075, 0.75]$
 $Q^2 = [1, 200]$

5× the number of protons per fill,
1.5 × faster cycle time
66% uptime per year

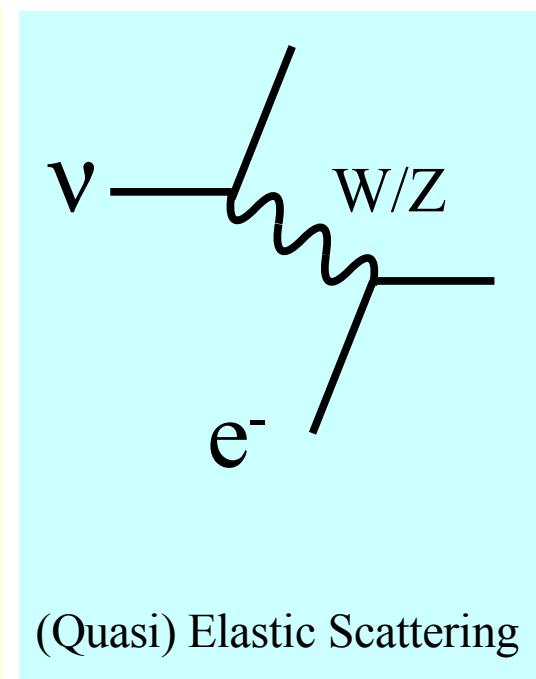
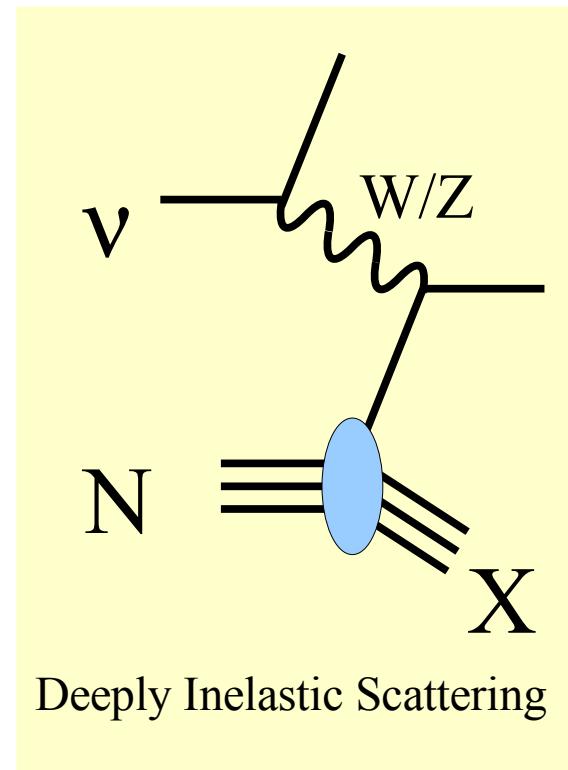
The goals were set in consultation with the Tevatron department to be ambitious but not outrageous.



NuSONG: High Statistics

NuSONG (*~5 year run*)

Events	Process
600 M	$\nu_\mu N \rightarrow \mu^- X$
190 M	$\nu_\mu N \rightarrow \nu_\mu X$
75 K	$\nu_\mu e^- \rightarrow \nu_\mu e^-$
700 K	$\nu_\mu e^- \rightarrow \mu^- \nu_e$
33 M	$\bar{\nu}_\mu N \rightarrow \mu^+ X$
12 M	$\bar{\nu}_\mu N \rightarrow \bar{\nu}_\mu X$



DIS Comparisons: *Charged Current*

Experiment	v DIS events	anti-v DIS events	Target	Isoscalar correction
CCFR	1.03 M	0.179 M	iron	5.67%
NuTeV	1.3 M	0.4 M	iron	5.74%
NuSONG	600 M	33 M	glass	0%

<http://prola.aps.org/pdf/PRD/v64/i11/e112006>

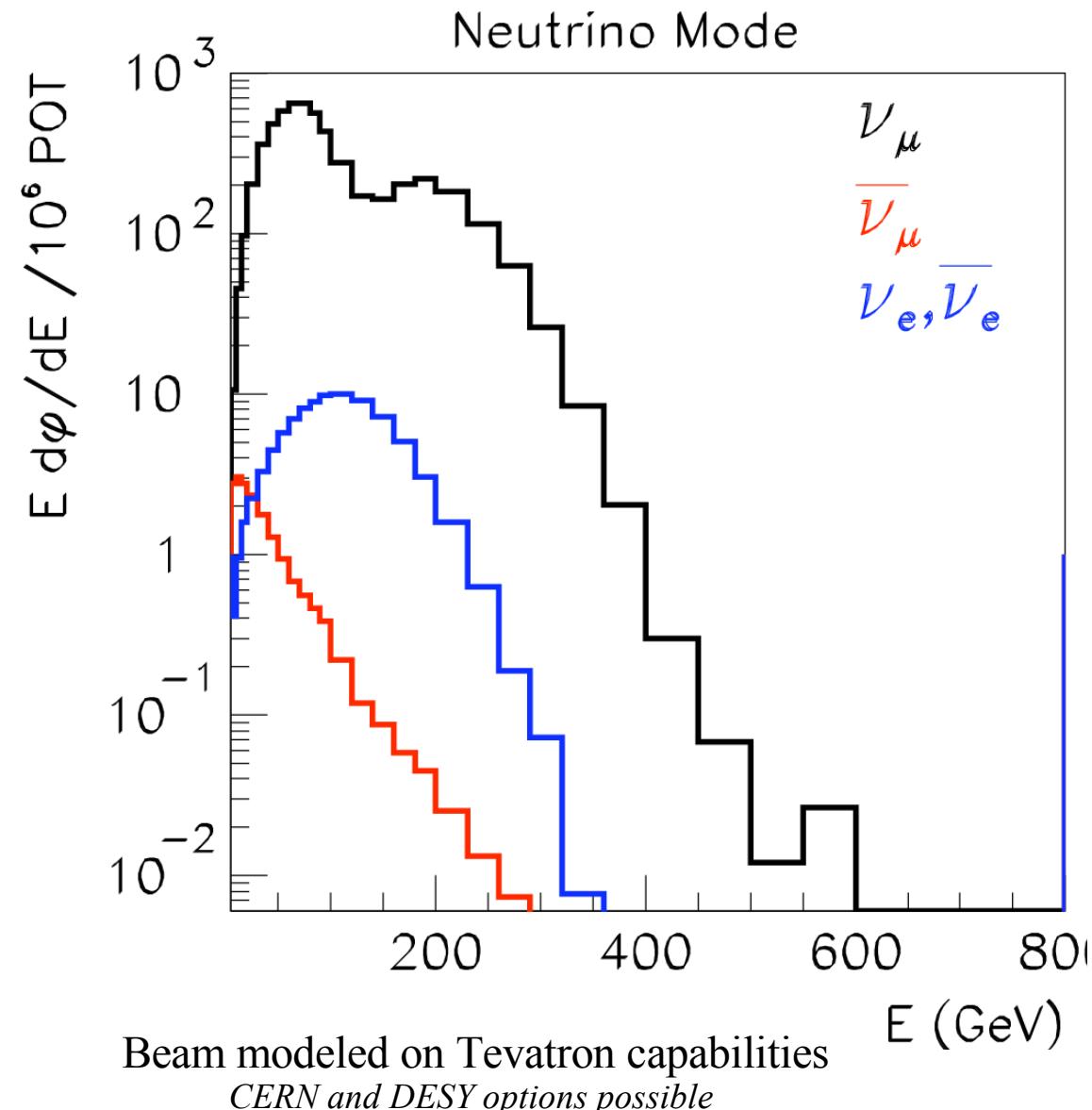
<http://prola.aps.org/pdf/PRL/v87/i25/e251802>

MINERvA Comparisons

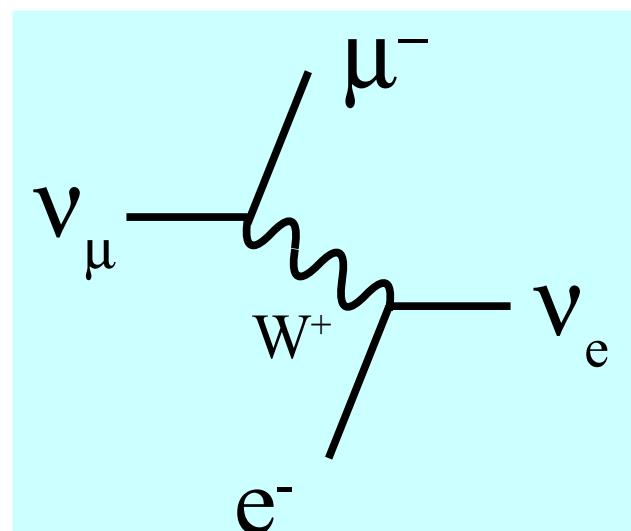
Target	Mass (Tons)	Events
Fe	0.70	2 M
Pb	0.85	2.5 M
He	0.40	600 K
C	0.15	430 K
CH	3	9 M

<http://minerva.fnal.gov/>

Broad $\{x, Q\}$ range
 Heavy Quarks @ threshold
 PDFs across wide x-range



Inverse Muon Decay (IMD)
 Precision EW searches
 Normalizing ES & IMD



Inverse Muon Decay (IMD)
 $E_\nu \gtrsim 11 \text{ GeV}$

The Measurements

$$\frac{d^2\sigma^{\nu(\bar{\nu})N}}{dx dy} \sim \left[\left(\frac{y^2}{2 + 2R_L} + 1 - y \right) F_2 \pm y \left(1 - \frac{y}{2} \right) x F_3 \right]$$

Neutrino data essential for PDF extraction

Parton Distribution Functions PDFs essential for Hadron measurements

$$F_2^\nu \sim [d + s + \bar{u} + \bar{c}]$$

$$F_2^{\bar{\nu}} \sim [\bar{d} + \bar{s} + u + c]$$

$$R_L = \frac{\sigma_L}{\sigma_T}$$

$$F_2^{\ell^\pm} \sim \left(\frac{1}{3}\right)^2 [d + s] + \left(\frac{2}{3}\right)^2 [u + c]$$

Neutrinos provide different linear combinations – key for flavor differentiation

Myth #1:

I thought we did
that already?

We did, but with assumptions

$$F_2^\nu = F_2^{\bar{\nu}}$$

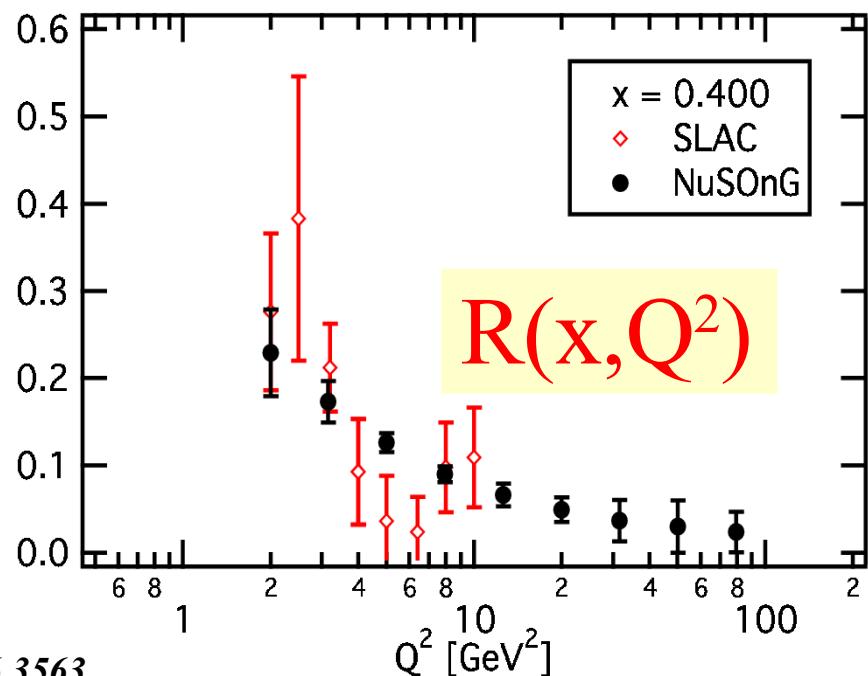
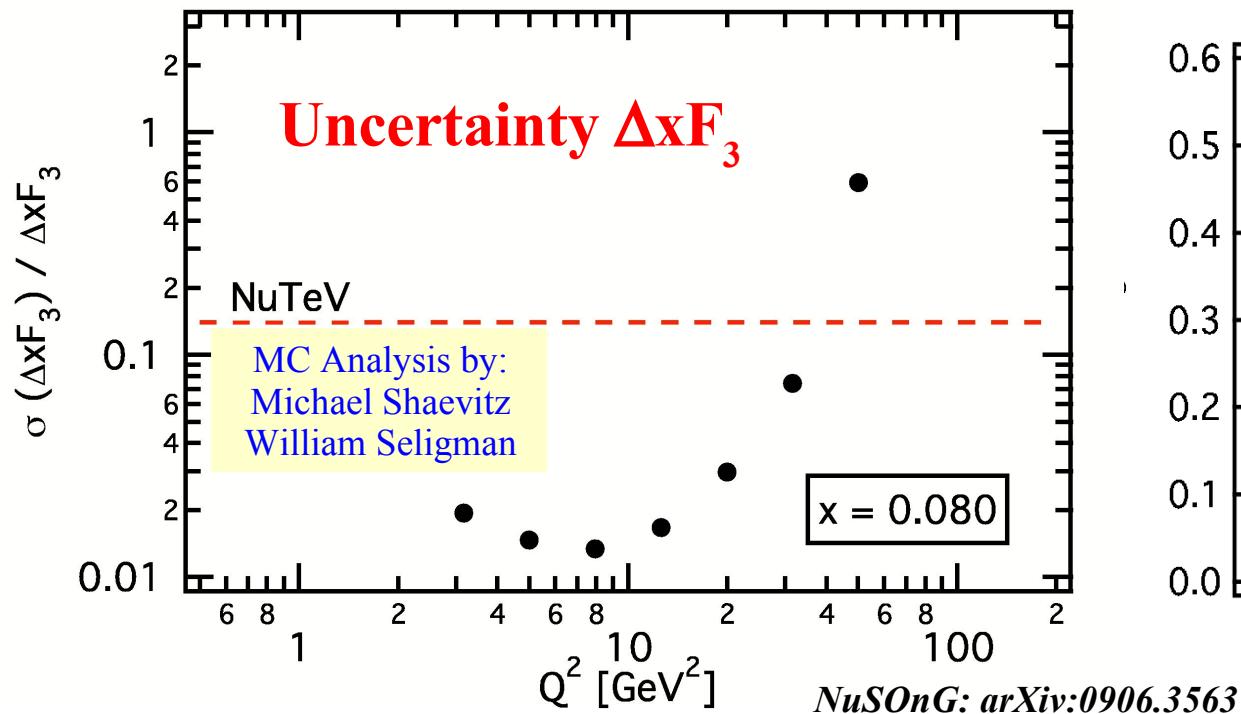
$$R_L^{\ell^\pm} = R_L^\nu = R_L^{\bar{\nu}}$$

$$u_{\text{proton}} = d_{\text{neutron}}$$

Myth #2: It doesn't matter

Independent Extraction is Feasible

NuSONG: Independent Extraction of: $\{F_2, xF_3, R\}$



Previous analysis:

For example: $R(x, Q^2)$ taken from charged lepton scattering ($e-p$ & $e-d$) in 1970-1985

$x=[0.1, 0.9]$

$Q^2=[0.6, 20]$

L.W.Whitlow et al.,
Phys.Lett.B250:193-198,1990.

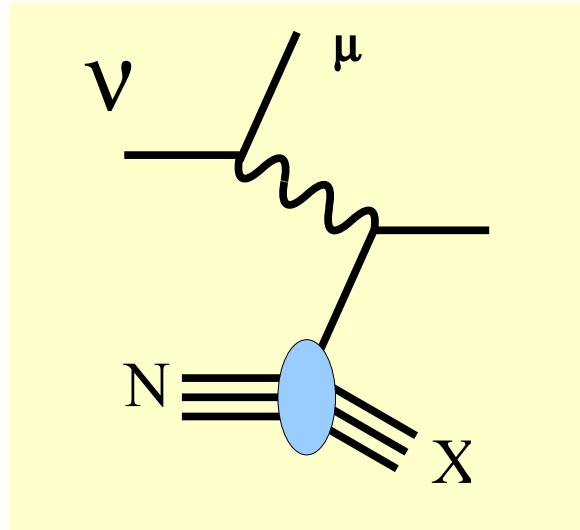
An Example:

Why “one size”
does not fit all

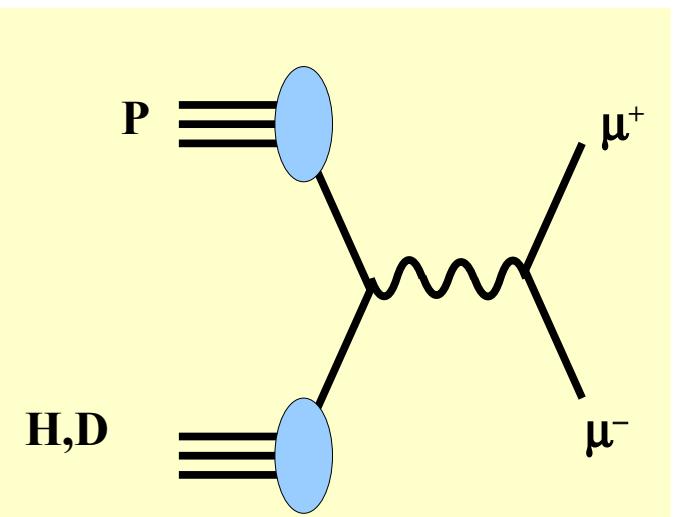
Why do we need an independent
Structure Function extraction?

Extend CTEQ6 PDFs with New & Updated Data Sets

Deeply Inelastic Scattering



Drell-Yan



NuTeV

Neutrinos on Iron
 $\langle E_\nu \rangle = 120$ GeV
 860K nu
 230K nubar
 1170+966 points

Chorus

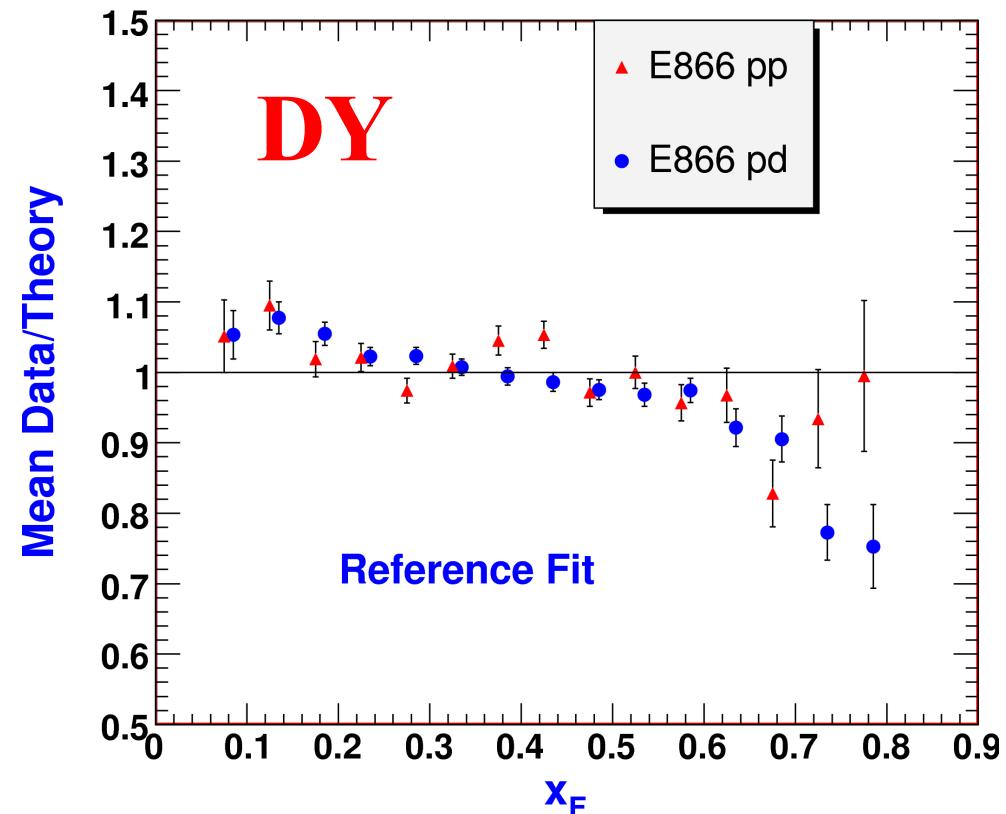
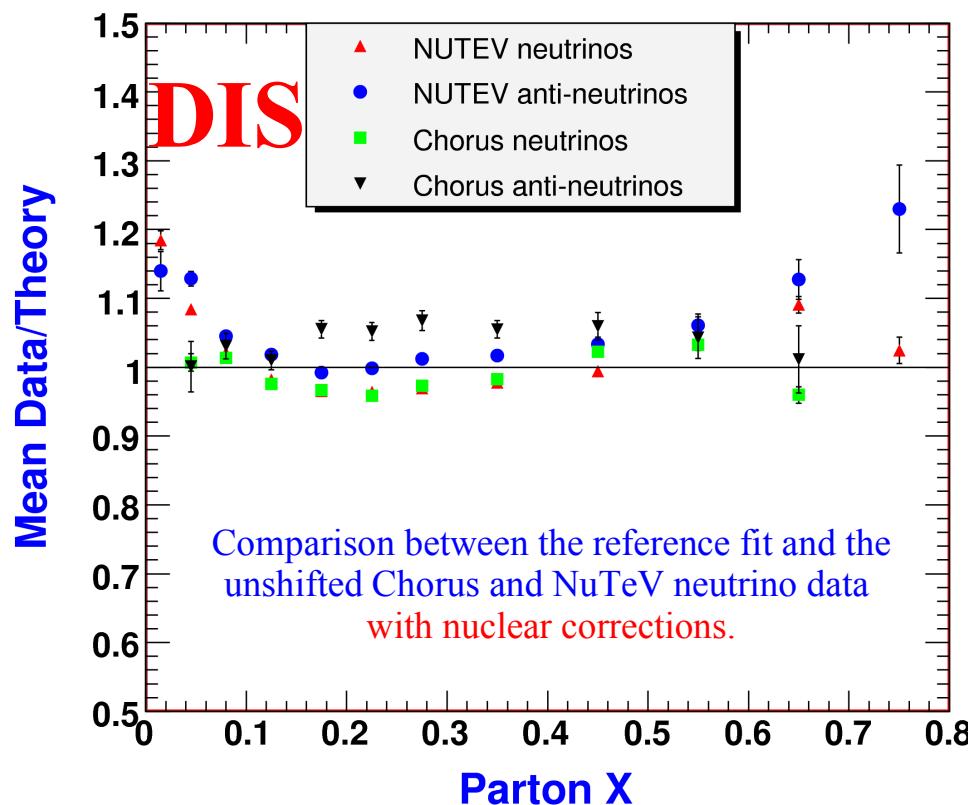
Neutrinos on lead
 $0.01 < x < 0.7$
 $10 < E_\nu < 200$ GeV
 $p_\mu > 5$ GeV
 412 points

E866 NuSea:

800 GeV proton beam
 on hydrogen & deuterium
 140K DY muon pairs
 $M_{\mu\mu} > 4.5$ GeV (*Hi Mass*)
 $0.020 < x < 0.345$
 184+191 points

Could nuclear corrections be different for CC (W) or NC (γ ,Z) processes???

19



“Thus, these results suggest on a purely phenomenological level that the nuclear corrections may well be very similar for the nu and nubar cross sections and that the overall magnitude of the corrections may well be smaller than in the model used in this analysis.”

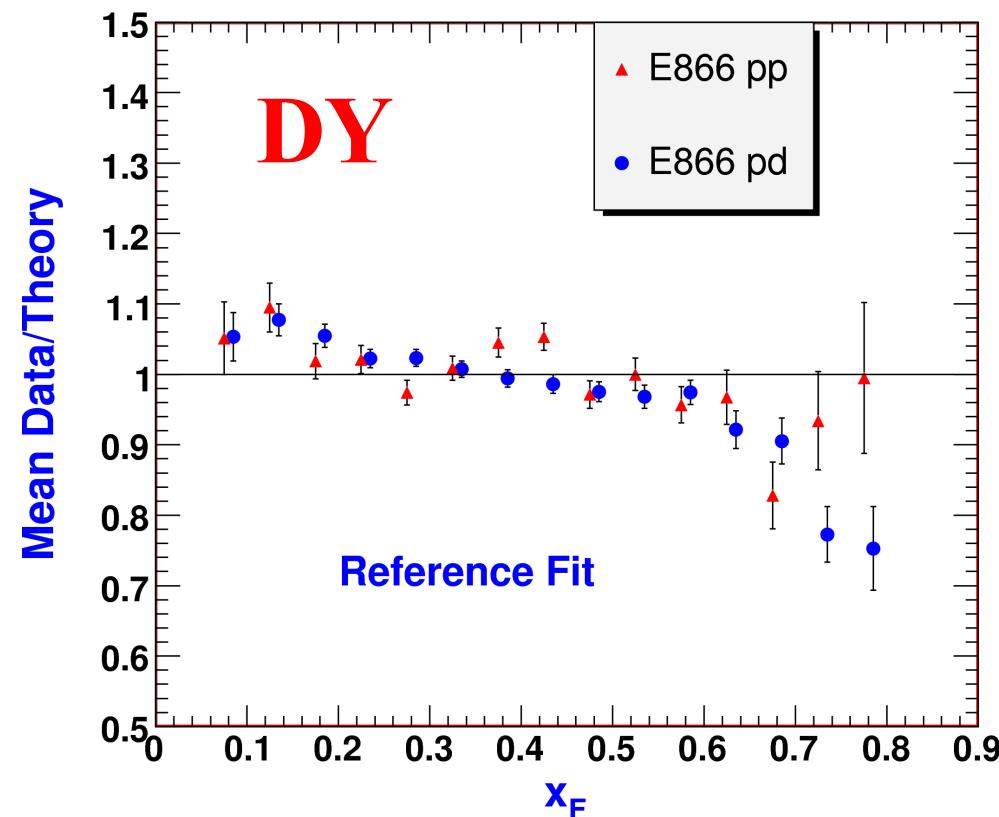
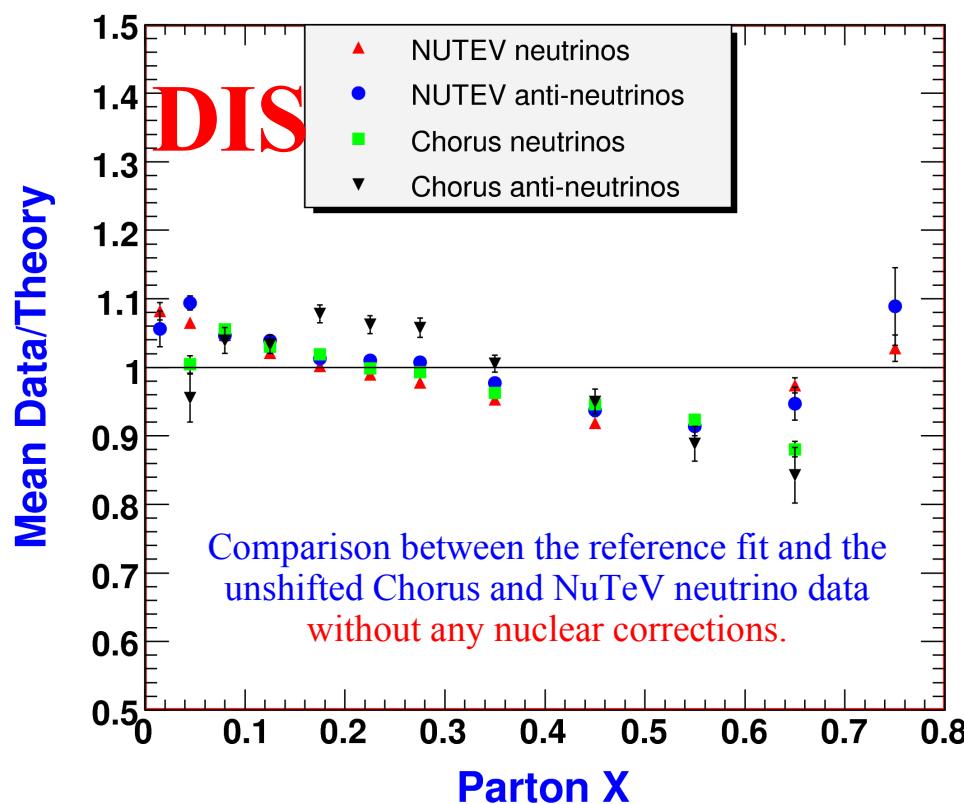
$\chi=7453/5062$ Reference Fit

$\chi=6606/5062$ Mod Nuclear Fit

Owens, Huston, Keppel, Kuhlmann,
Morfin, Olness, Pumplin, Stump.
Phys.Rev.D75:054030,2007.

Could nuclear corrections be different for CC (W) or NC (γ ,Z) processes???

20



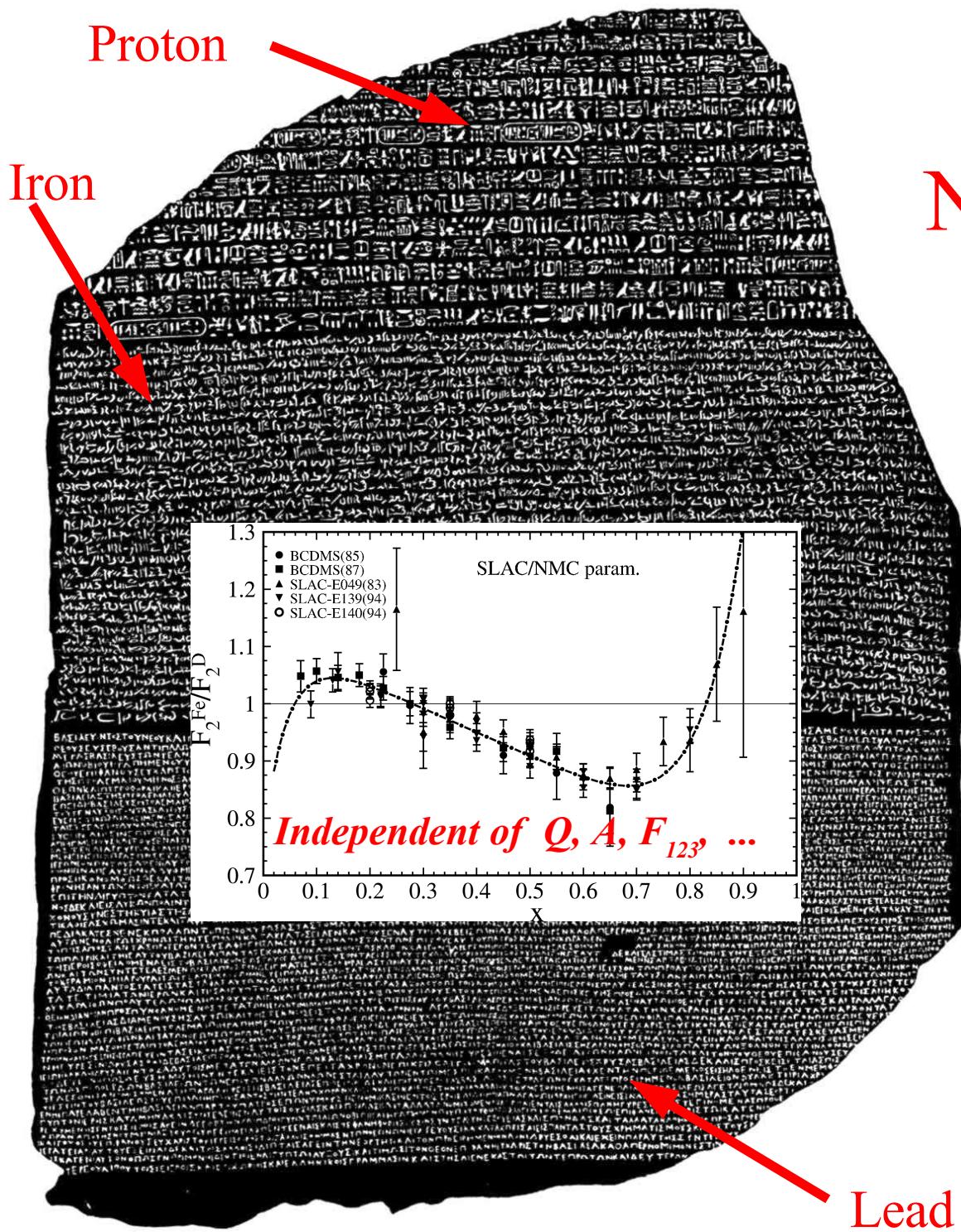
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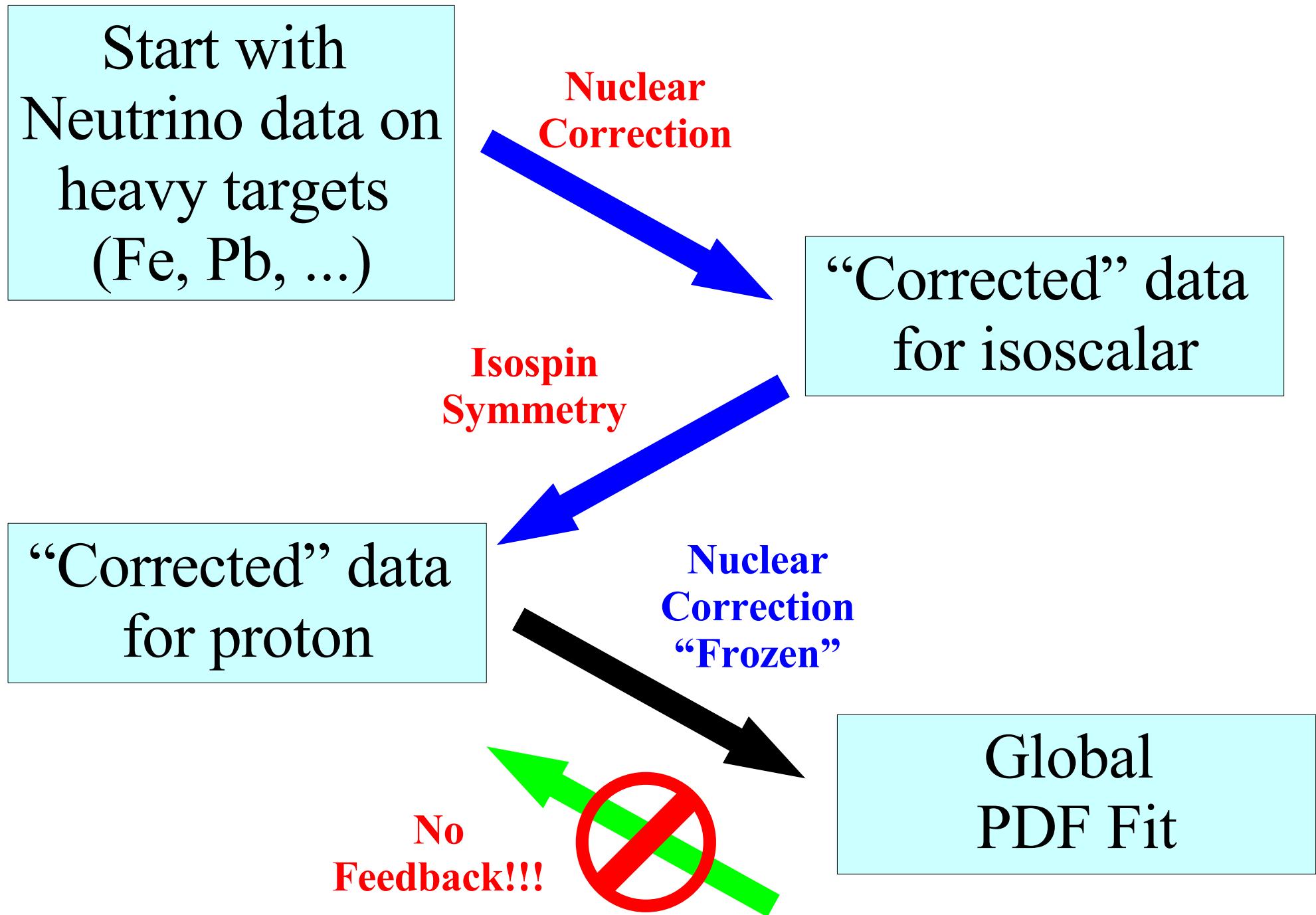
Where do nuclear
corrections come
from???



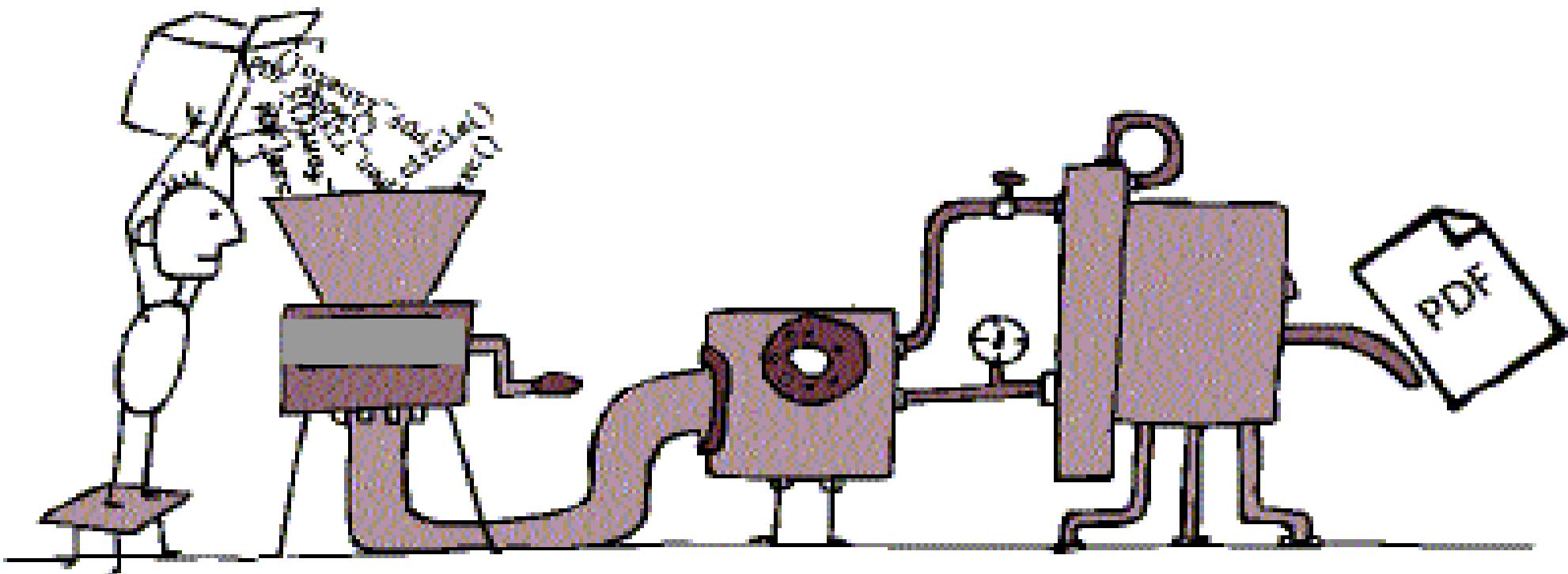
Where do Nuclear Corrections come from ???

carved in stone

Discovered by the French in 1799 at Rosetta, a harbor on the Mediterranean coast in Egypt. Comparative translation of the stone assisted in understanding many previously undecipherable examples of hieroglyphics.



Include Nuclear Dimension Dynamically



Extended CTEQ Framework

- ✓ CTEQ style global fit extended
handle various nuclear targets
- ✓ CTEQ Data + nuclear DIS & DY
[~15 targets; ~2000+ data]
- ✓ A-dependence modeled;
NLO fits work well

A-Dependent PDFs

$$x f(x) = x^{a_1} (1-x)^{a_2} e^{a_3 x} (1 + e^{a_4 x})^{a_5}$$

$$a_i \rightarrow a_i(A)$$

$$a_k = a_{k,0} + a_{k,1} (1 - A^{-a_{k,2}})$$

Observable	Experiment	Ref.	# data	χ^2 A1L	χ^2 A1M	χ^2 A1A	ID
F_2^A/F_2^D :							
He/D	SLAC-E139	[18]	18	9.8	6.82	6.28	5141
	NMC-95,re	[19]	16	35.6	16.91	18.31	5124
	Hermes	[20]	92	134.0	72.14	71.05	5156
Li/D	NMC-95	[21]	15	45.0	18.80	19.68	5115
Be/D	SLAC-E139	[18]	17	52.7	21.48	20.75	5138
C/D	EMC-88	[22]	9	10.3	7.28	7.11	5107
	EMC-90	[23]	2	0.2	0.14	0.11	5110
	SLAC-E139	[18]	7	31.3	4.06	4.51	5139
	NMC-95,re	[19]	16	13.9	16.12	16.62	5114
	NMC-95	[21]	15	13.9	7.13	7.26	5113
	FNAL-E665-95	[24]	4	23.4	8.81	8.29	5125
N/D	BCDMS-85	[25]	9	12.1	6.94	7.26	5103
	Hermes	[20]	92	94.5	62.42	58.94	5157
Al/D	SLAC-E049	[26]	18	32.2	20.42	20.38	5134
	SLAC-E139	[18]	17	22.12	6.60	8.05	5136
Ca/D	EMC-88	[23]	2	5.5	1.47	1.37	5109
	SLAC-E139	[18]	7	14.2	2.07	1.53	5140
	NMC-95,re	[19]	15	48.6	12.75	13.74	5121
	FNAL-E665-95	[24]	4	16.2	7.88	7.67	5126
Fe/D	BCDMS-85	[25]	6	5.3	3.91	4.39	5102
	BCDMS-87	[27]	10	36.0	8.58	9.81	5101
	SLAC-E049	[28]	14	8.8	10.39	6.24	5131
	SLAC-E139	[18]	23	43.4	35.14	35.31	5132
	SLAC-E140	[29]	6	16.8	2.93	4.87	5133
Co/D	EMC-88	[22]	9	7.1	4.24	4.47	5106
	EMC-93(addendum)	[30]	10	14.4	6.13	6.89	5104
	EMC-93(chariot)	[30]	9	9.8	6.18	6.53	5105
Kr/D	Hermes	[20]	84	120.7	64.53	62.98	5158
Ag/D	SLAC-E139	[18]	7	22.5	4.04	2.88	5135
Sn/D	EMC-88	[22]	8	28.3	19.82	20.09	5108
Xe/D	FNAL-E665-92(em cut)	[31]	4	4.0	0.65	0.61	5127
Au/D	SLAC-E139	[18]	18	48.6	8.22	7.89	5137
Pb/D	FNAL-E665-95	[24]	4	20.3	7.77	7.45	5129

$F_2^A/F_2^{A'}$:							
Be/C	NMC-95	[32]	15	14.3	5.87	5.82	5112
Al/C	NMC-95	[32]	15	14.1	5.17	5.19	5111
Ca/C	NMC-95	[18]	20	21.7	31.47	35.73	5120
	NMC-95	[32]	15	19.8	5.39	5.31	5119
Fe/C	NMC-95	[32]	15	25.9	9.54	9.35	5143
Sn/C	NMC-95	[33]	144	312.5	102.82	96.29	5159
Pb/C	NMC-95	[32]	15	13.4	7.31	8.09	5116
C/Li	NMC-95	[18]	20	49.7	21.82	20.37	5123
Ca/Li	NMC-95	[18]	20	38.3	24.62	23.53	5122

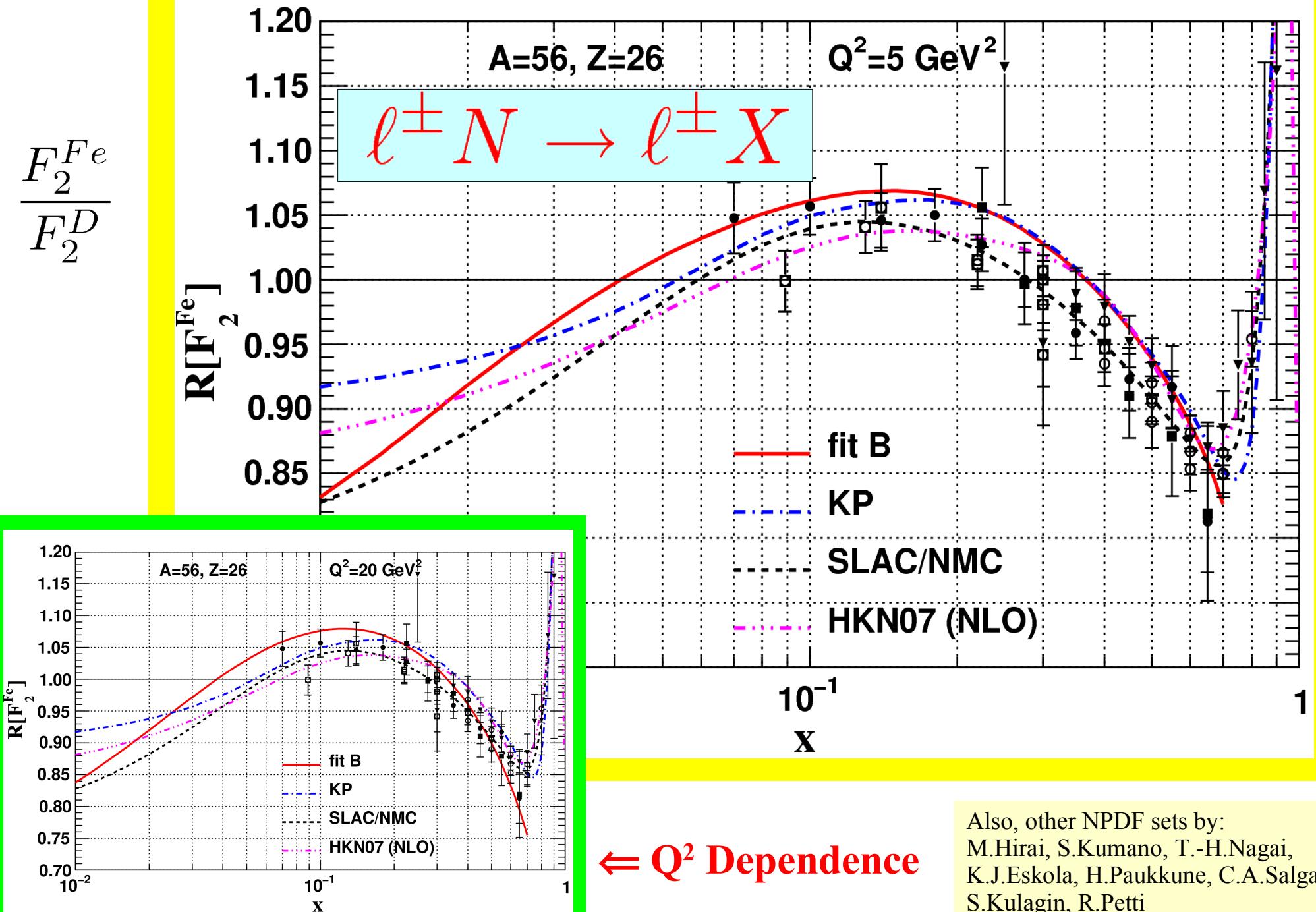
$\sigma_{DY}^{PA}/\sigma_{DY}^{PA'}$:							
C/D	FNAL-E7						
Ca/D	FNAL-E7						
Fe/D	FNAL-E7						
W/D	FNAL-E7						
Fe/Be	FNAL-E8						
W/Be	FNAL-E8						
Total:							

Also, other NPDF sets by:
 M.Hirai, S.Kumano, T.-H.Nagai,
 K.J.Eskola, H.Paukkune, C.A.Salgado,
 S.Kulagin, R.Petti

Nuclear PDFs from neutrino deep inelastic scattering.

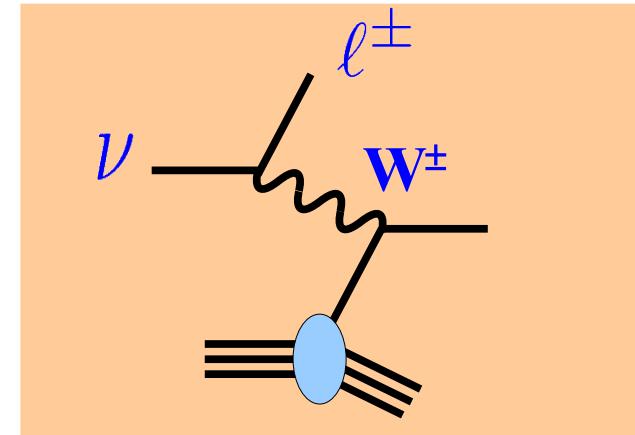
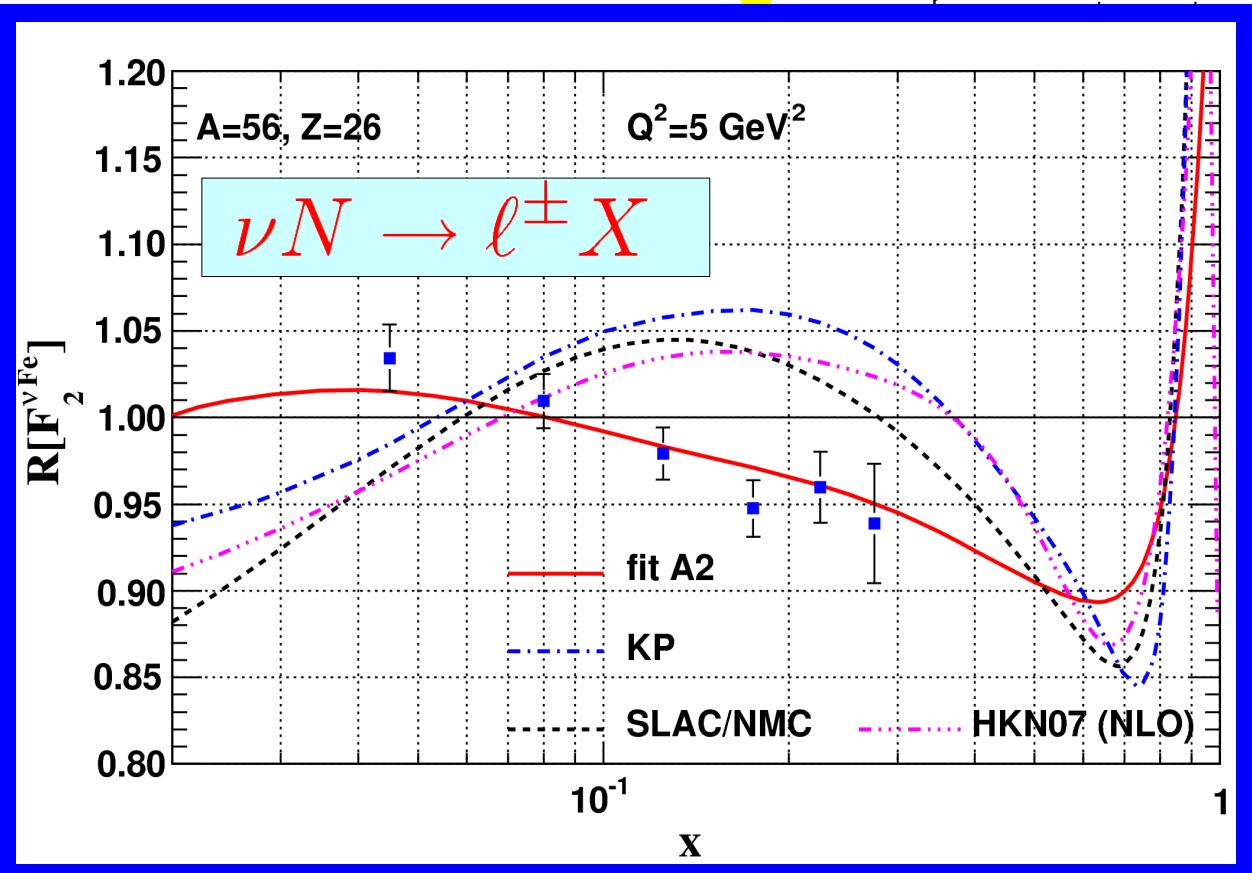
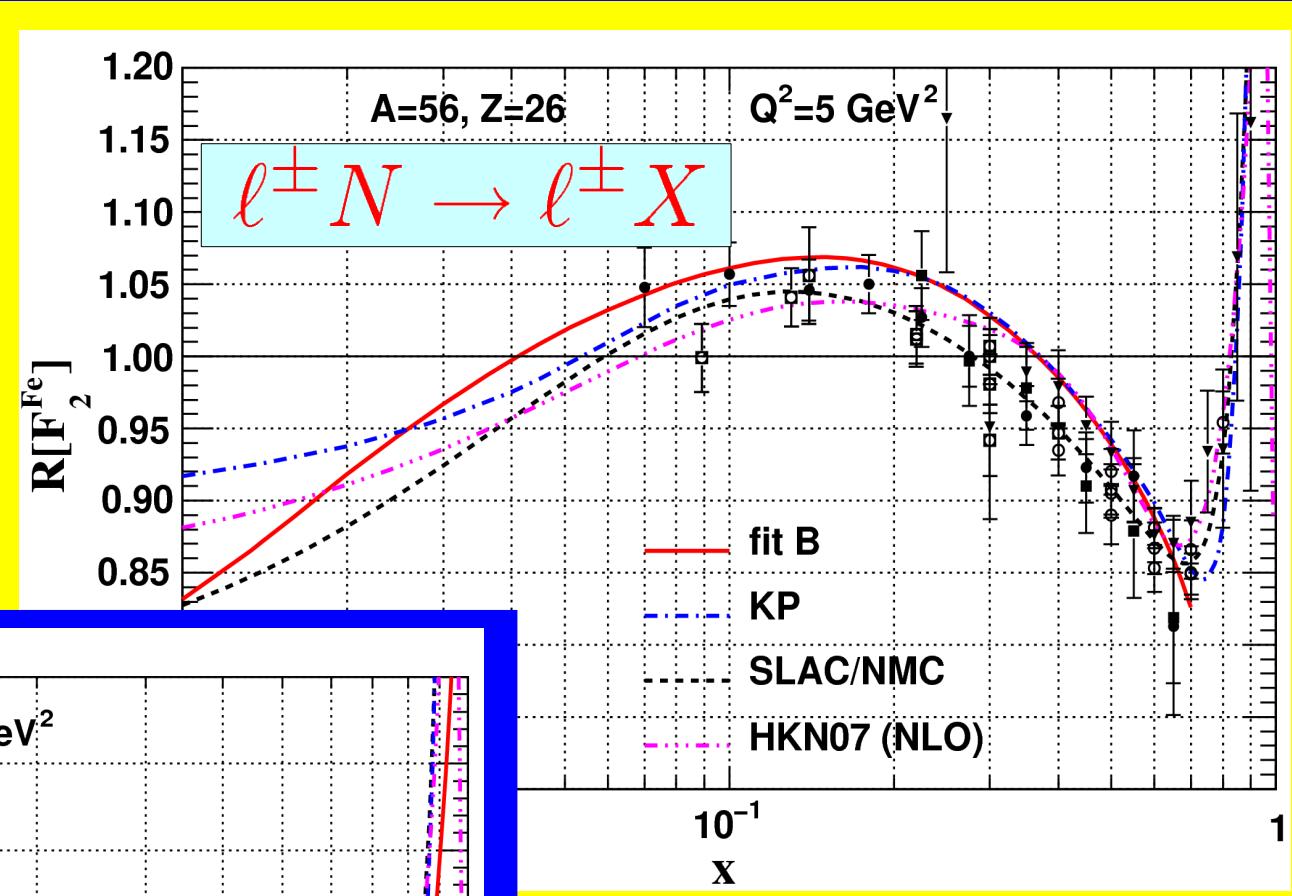
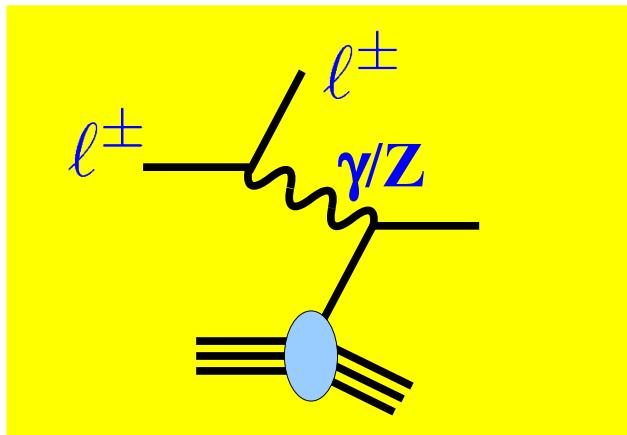
I. Schienbein, J.Y. Yu, C. Keppel, J.G. Morfin, F. Olness, J.F. Owens.
 Phys.Rev.D77:054013,2008.

Nuclear Corrections: Charged Lepton (γ) Case



Oooooops!

Charged Lepton DIS \Rightarrow



\Leftarrow Neutrino DIS

~~Myth~~ #1: $\{\nu, \bar{\nu}, \ell^\pm\}$ can be different

Independent extraction of $\{F_2, xF_3, R\}$ is necessary

Determine R and Nuclear modifications separately for: $\{\nu, \bar{\nu}, \ell^\pm\}$

~~Myth~~ #2: It does matter

E.g., CTEQ6.5 and beyond do not use heavy target ν DIS data

PDF sets used for Tevatron & LHC are without this flavor differentiation

NuSOnG will have stats to resolve this:

Separate “A” and $\{\nu, \bar{\nu}, \ell^\pm\}$ Dependence

Alternative Target Materials:

58k ν and 30k $\bar{\nu}$ -bar events per ton

Material	Mass of 1" slab (tons)	# slabs for 3M ν DIS
C	1.6	33
Al	1.9	27
Fe	5.5	10
Pb	7.9	7

Isospin & Heavy Quarks

Using $\Delta x F_3$ & ΔF_2

$$\Delta x F_3^A = x F_3^{\nu A} - x F_3^{\bar{\nu} A}$$

$$\Delta x \bar{F}_3$$

$$= 2 \frac{(N - Z)}{A} \left[(u_{p/A} - d_{p/A}) + (\bar{u}_{p/A} - \bar{d}_{p/A}) + \frac{1}{2} \delta I_A \right]$$

$$+ 2x s_A^+ - 2x c_A^+ + x \delta I_A$$

$\Rightarrow = 0$ for
isoscalar

Strange

Charm

Isospin

$$\delta I_A = (\delta d + \delta \bar{d}) - (\delta u + \delta \bar{u})$$

$$s_A^\pm = s_A(x) \pm \bar{s}_A(x)$$

$$\Delta F_2^A = \frac{5}{18} F_2^{CC}(x, Q^2) - F_2^{NC}(x, Q^2)$$

$$\Delta F_2$$

$$\simeq \frac{1}{6} x \frac{(N - Z)}{A} [(u_{p/A} - d_{p/A}) + (\bar{u}_{p/A} - \bar{d}_{p/A}) x]$$

$$+ \frac{1}{6} x s_A^+(x) - \frac{1}{6} x c_A^+(x) + \frac{1}{6} x \frac{N}{A} \delta I_A$$

$= 0$ for
isoscalar

Strange

Charm

Isospin

$$F_2^{CC,A} = \frac{1}{2} [F_2^{\nu A} + F_2^{\bar{\nu} A}]$$

Isospin Symmetry

... taken for granted

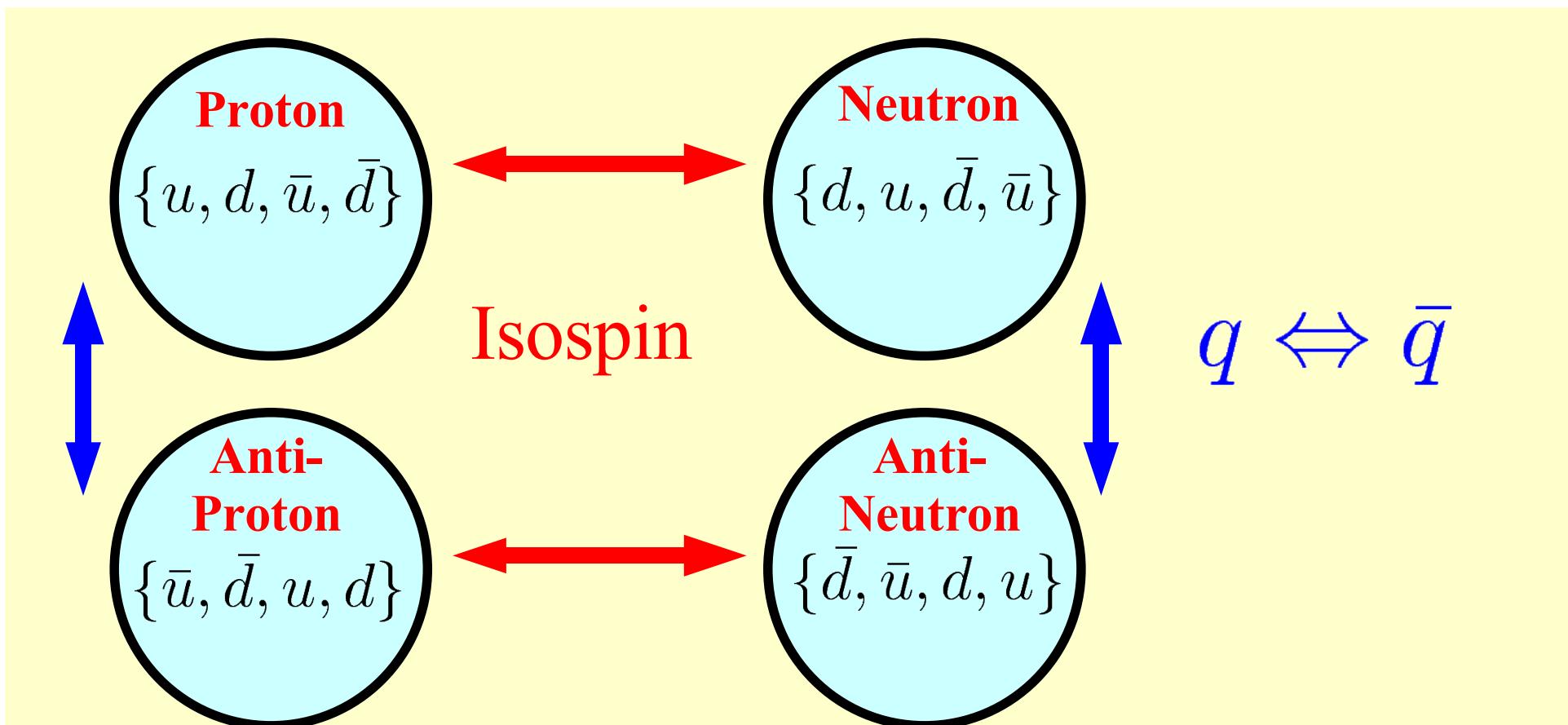
Isospin Symmetry used to relate PDFs

$$\Delta x F_3^A = x F_3^{\nu A} - x F_3^{\bar{\nu} A} = +2x s_A^+ - 2x c_A^+ + x \delta I_A$$

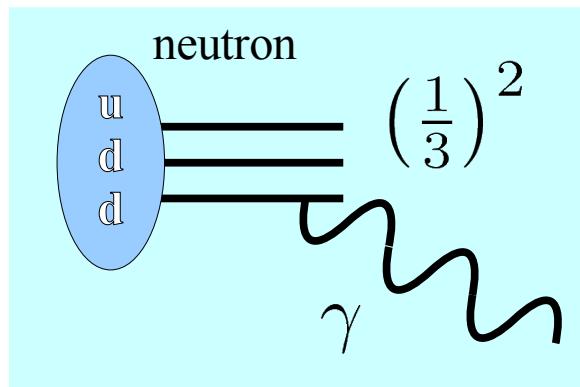
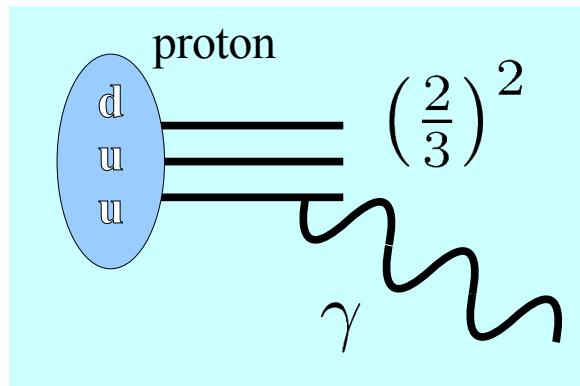
$$\Delta F_2^A = \frac{5}{18} F_2^{CC} - F_2^{NC} = +\frac{1}{6} x s_A^+(x) - \frac{1}{6} x c_A^+(x) + \frac{1}{6} x \frac{N}{A} \delta I_A$$

$$\delta I_A = (\delta d + \delta \bar{d}) - (\delta u + \delta \bar{u})$$

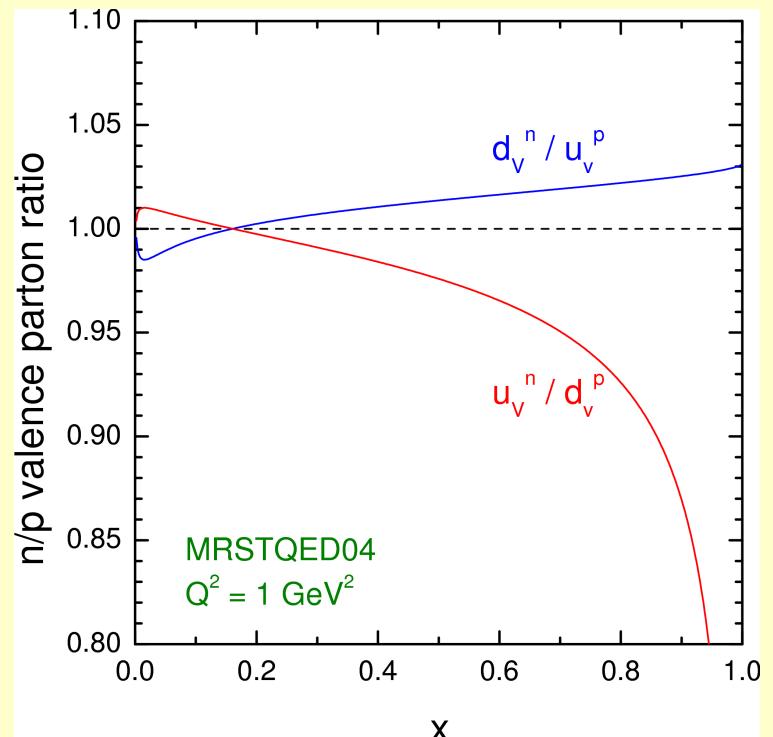
$$\delta u = \delta u_p - \delta d_n$$



Photon is not flavor blind!!!



MRST-QED 04



MRST, Eur.Phys.J.C39:155-161,2005.

Isospin terms are comparable to NNLO QCD

Could Isospin terms affect
Tevatron W-Asymmetry???

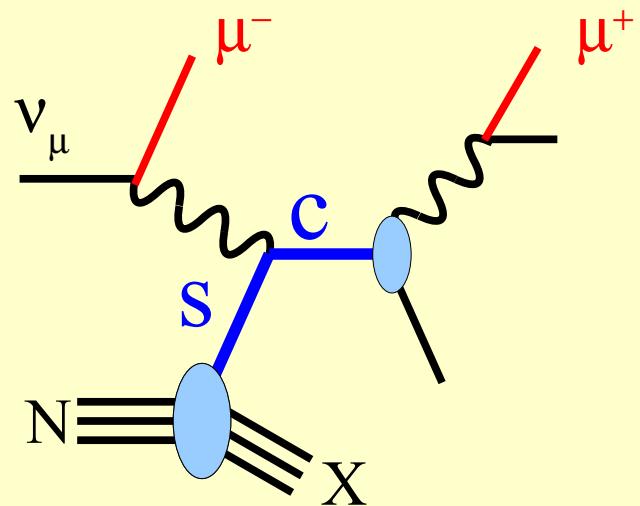
Heavy Quarks

$$\Delta x F_3^A = +2x s_A^+ - 2x c_A^+ + x \delta I_A$$

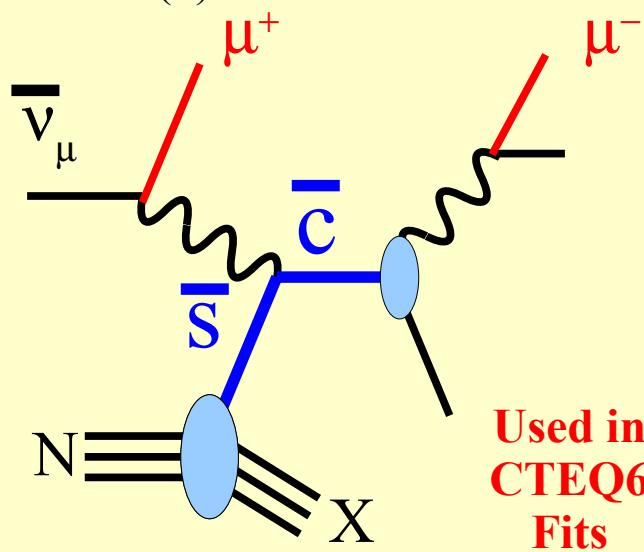
$$\Delta F_2^A = +\frac{1}{6}x s_A^+(x) - \frac{1}{6}x c_A^+(x) + \frac{1}{6}x \frac{N}{A} \delta I_A$$

Di-muon production \Rightarrow Best determination of s(x)

Extract $s(x)$

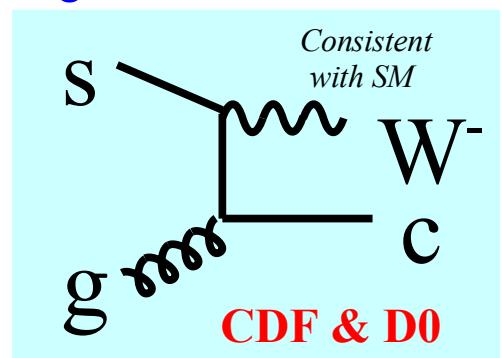


Extract $\bar{s}(x)$



Used in
CTEQ6
Fits

s \rightarrow Wc at the Tevatron

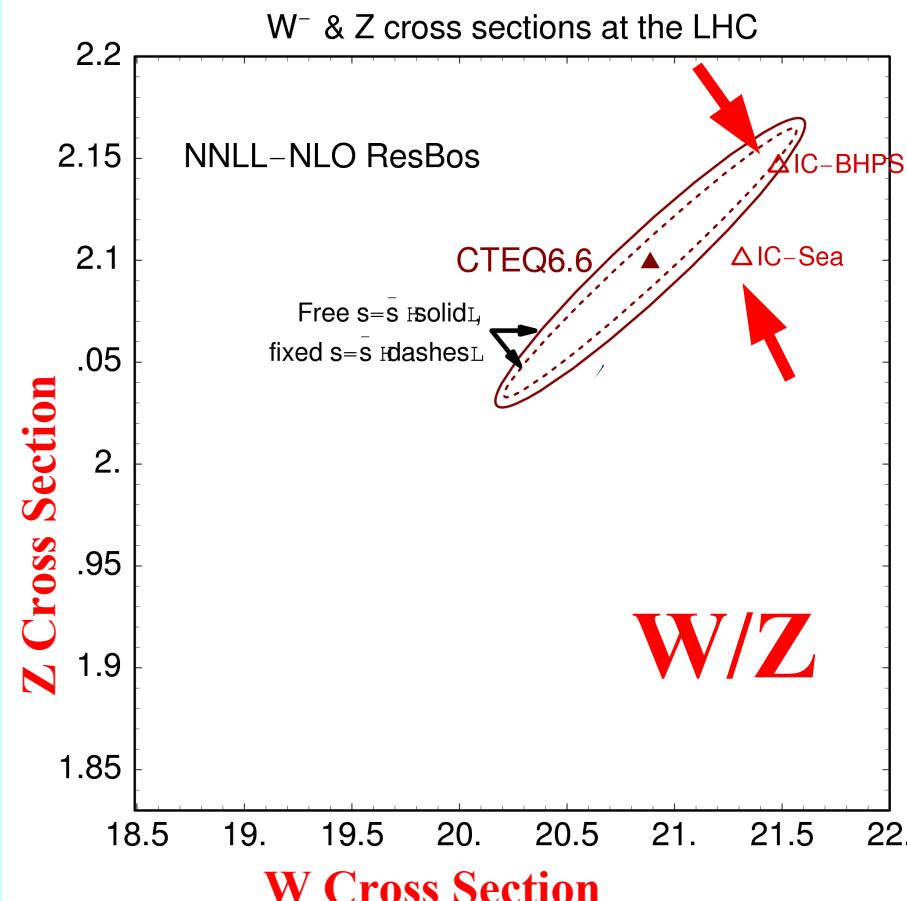
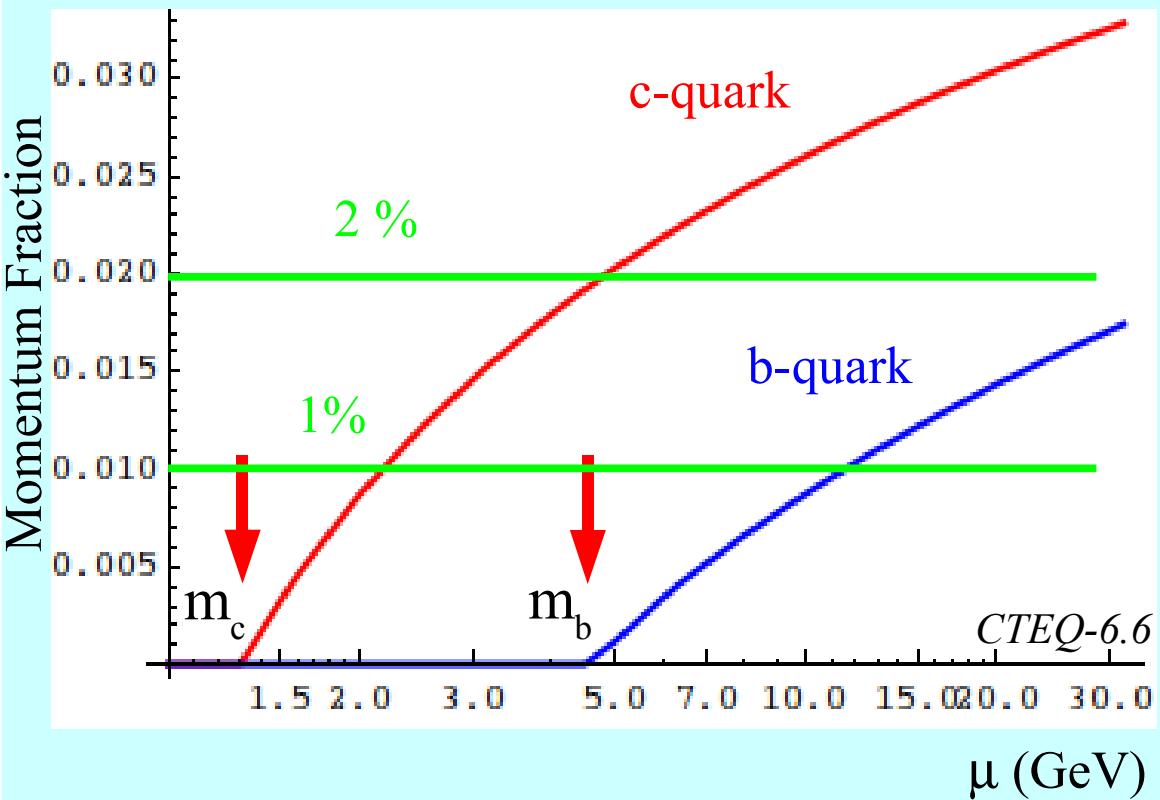


CDF: PRL 100:091803,2008.
D0: PLB666:23,2008.

$s(x)$ and $\bar{s}(x)$ are essential in extraction of $\sin\theta_W$

Are there Intrinsic Heavy Quarks??? Do they matter???

Are there Intrinsic Heavy Quarks???



- * Most sensitive near threshold
- * What happens if we allow the evolution to determine charm?

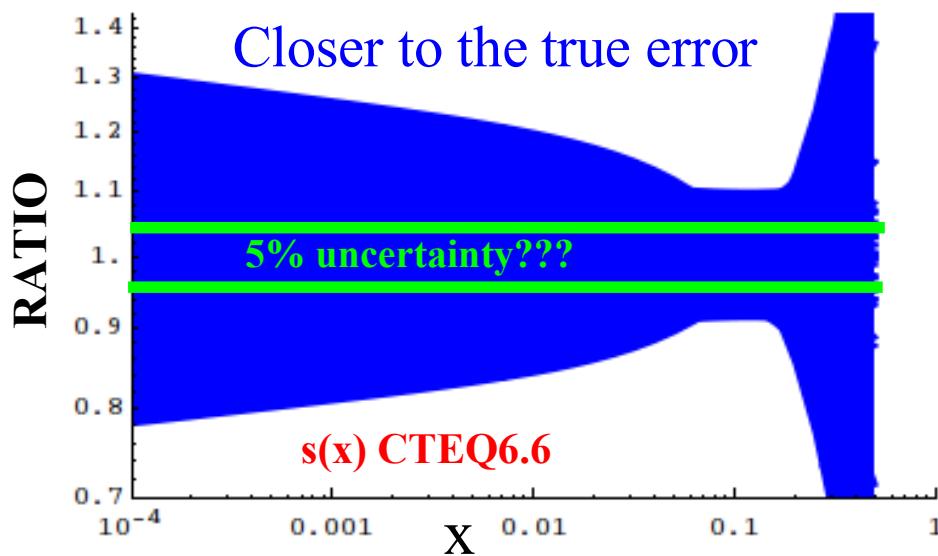
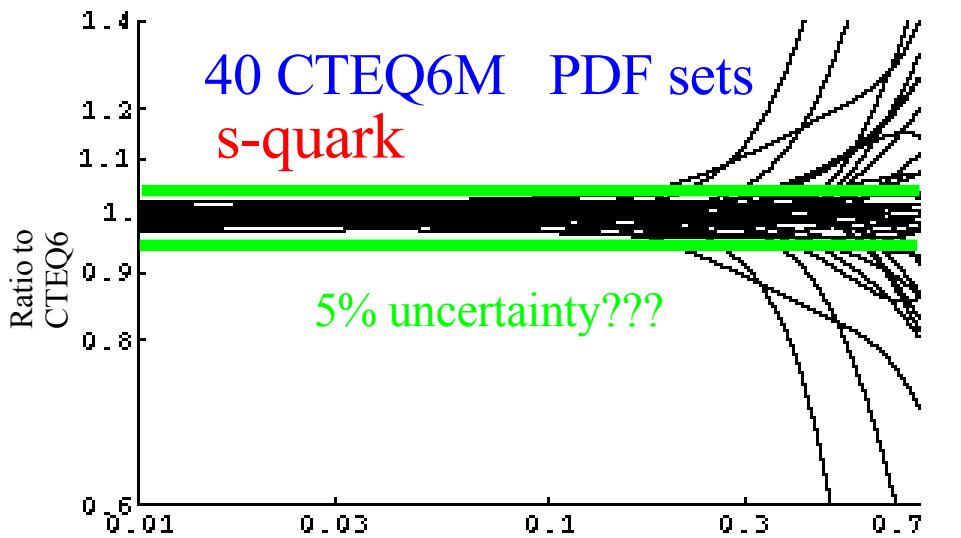
Zero: No intrinsic charm
 Positive: Intrinsic charm
 Negative: Inconsistent

Also, the 2-scale problem: $\{m, Q\}$

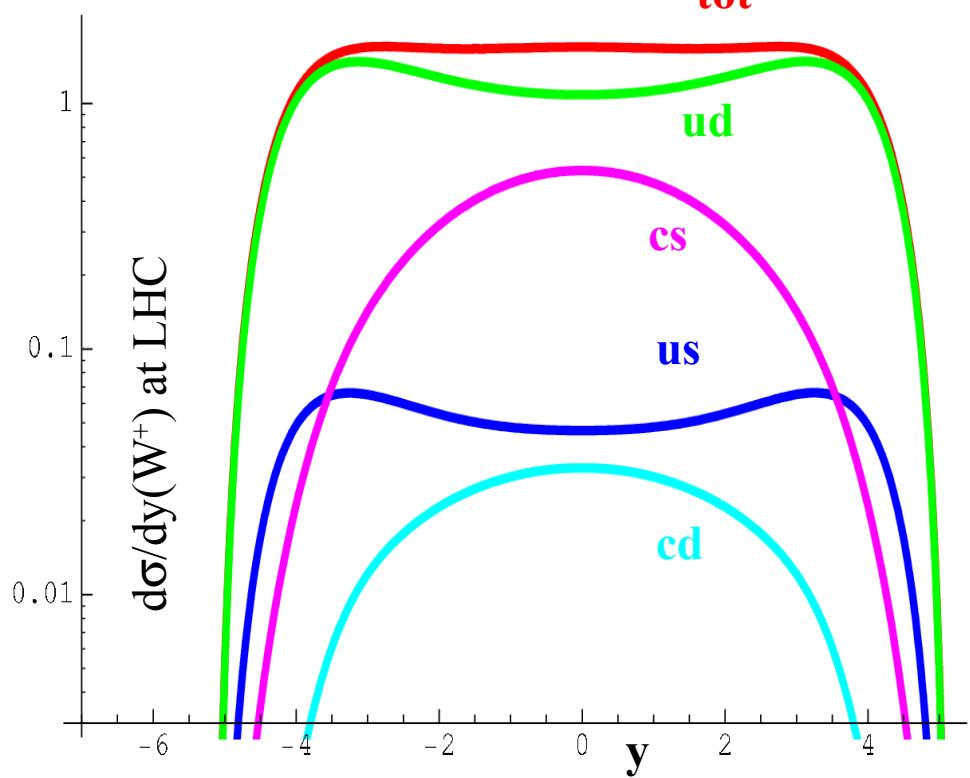
Nadolsky, et al., Phys.Rev.D78:013004,2008.
 J. Pumplin, Phys.Rev.D75:054029,2007.

W Production at LHC: A Benchmark Cross Section

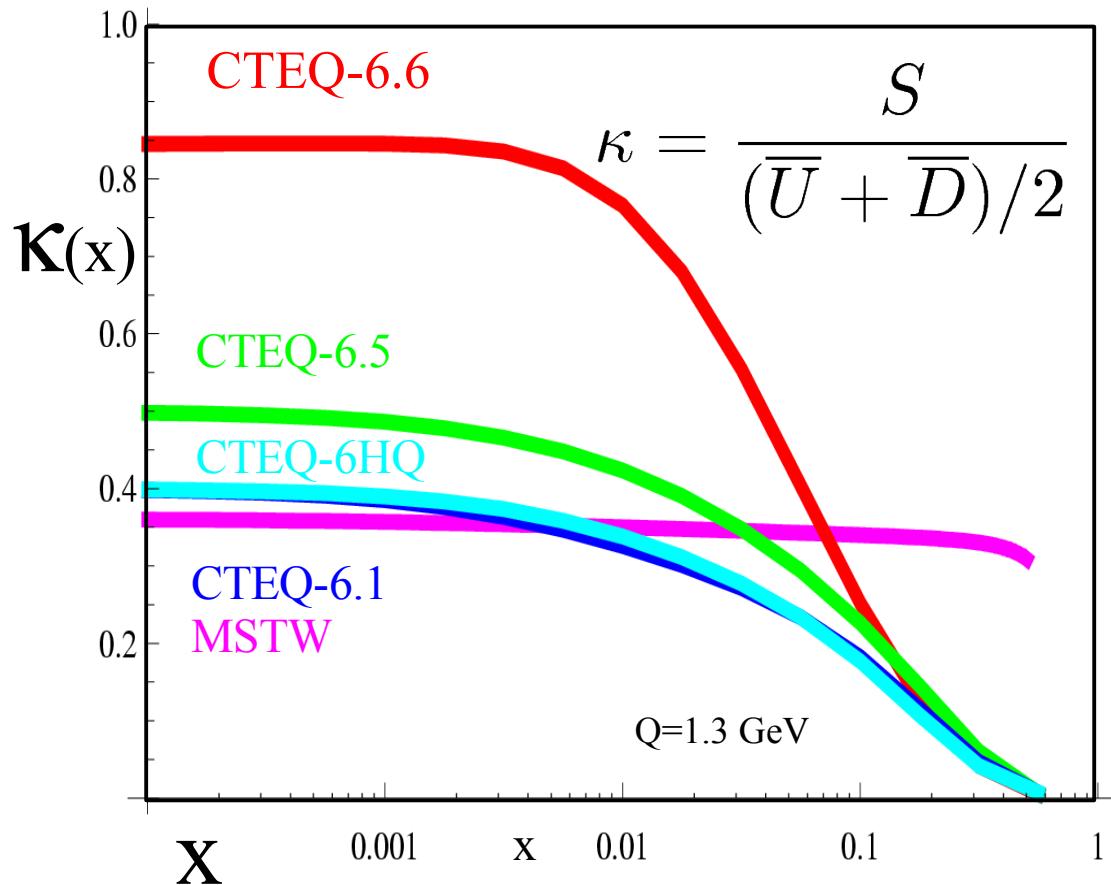
39



Heavy quark PDFs essential ingredient

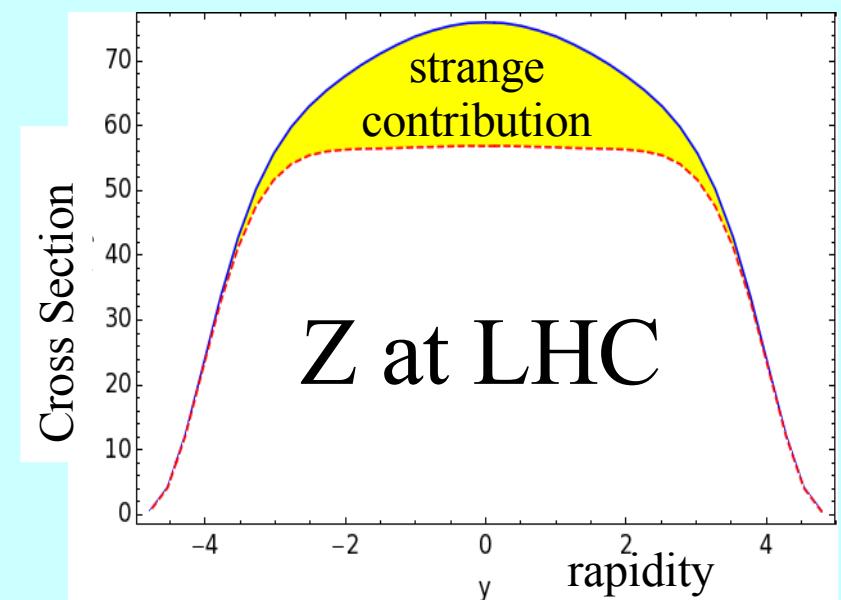
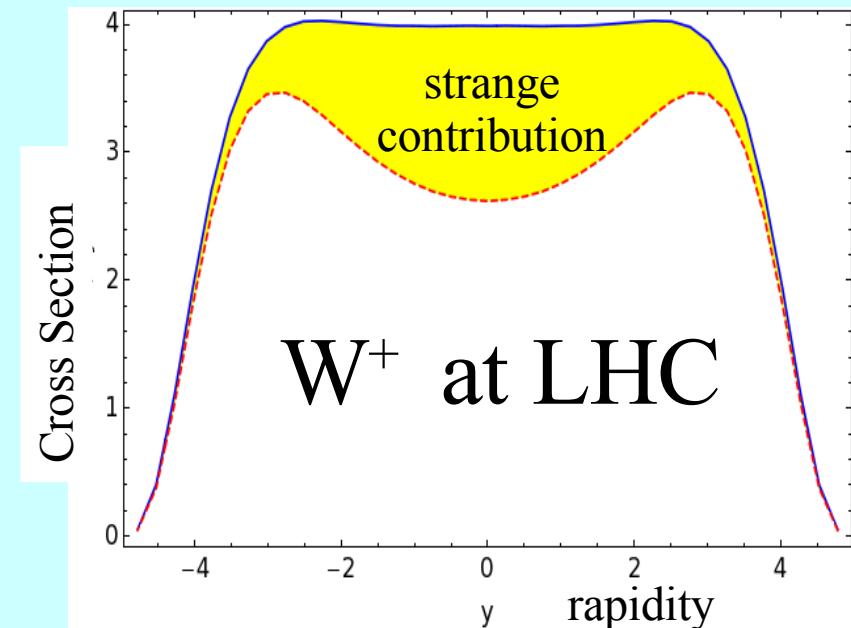


Heavy Quark components play an increasingly important role at the LHC



PDF Uncertainties will feed into
LHC ‘Benchmark’ processes

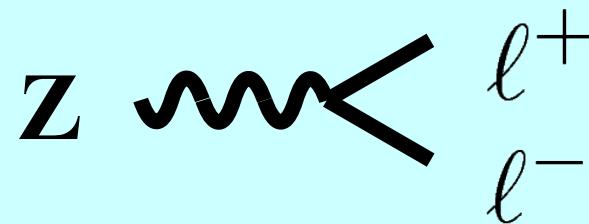
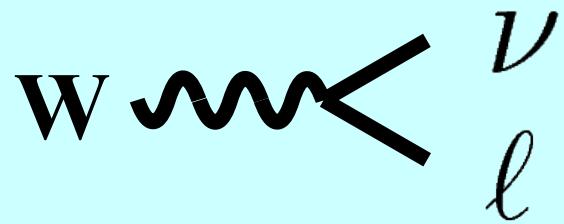
Comparison with new NNPDF sets: Les Houches 2009



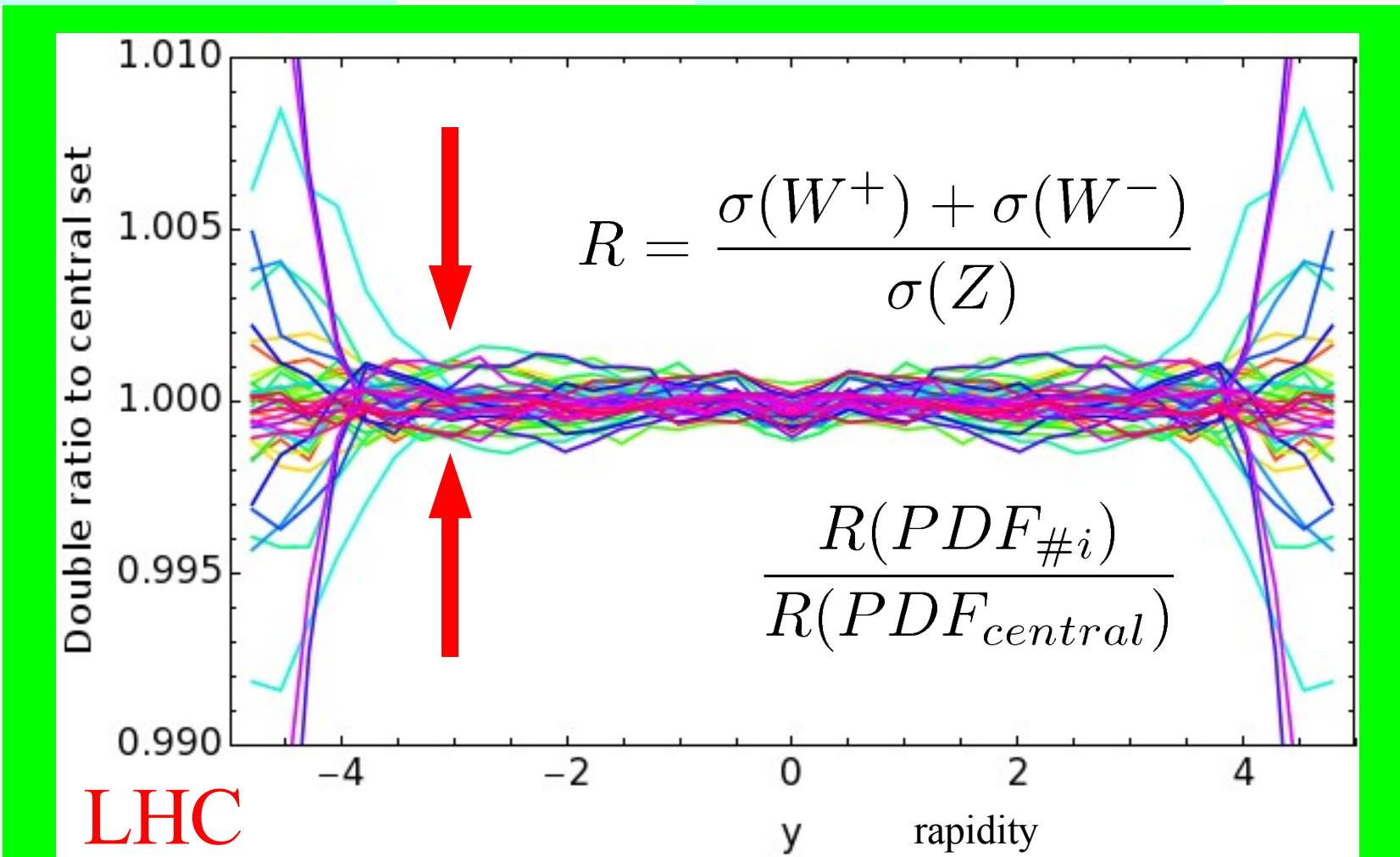
VRAP
Code

Anastasiou, Dixon, Melnikov, Petriello,
Phys.Rev.D69:094008,2004.

Use Z to calibrate W

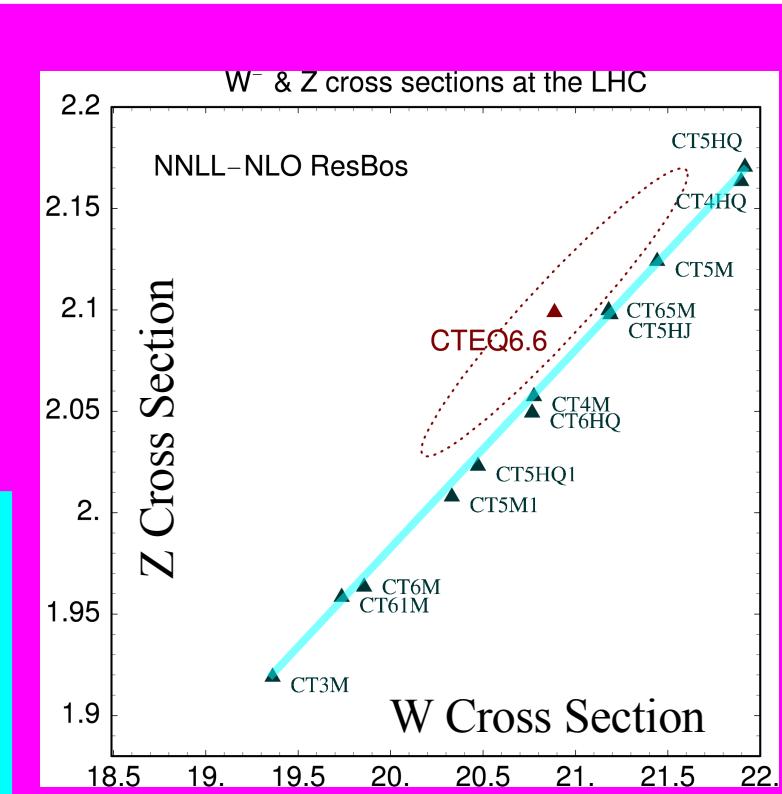
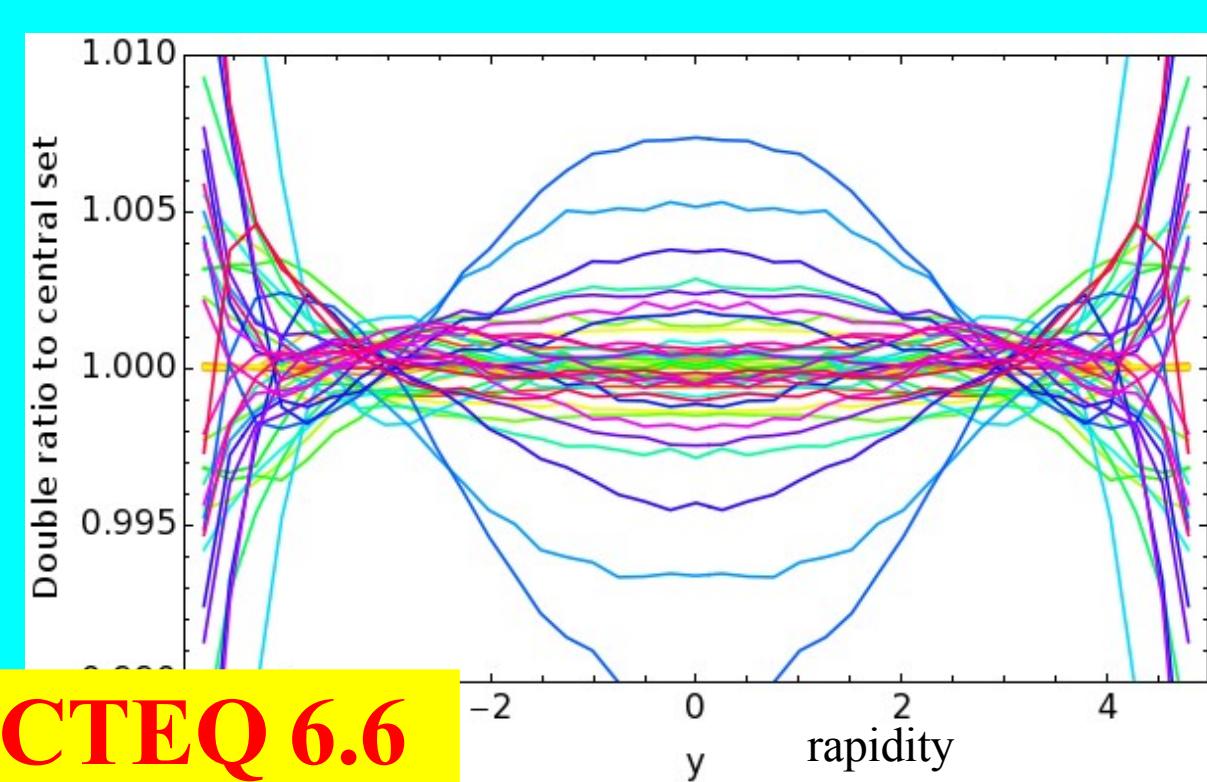
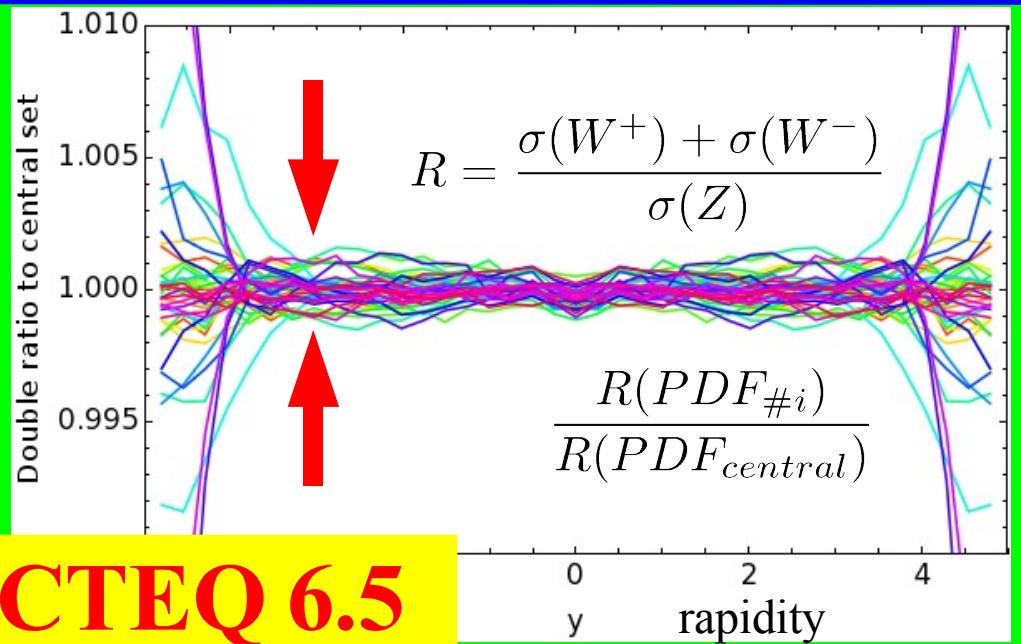


Useful for M_W
determination



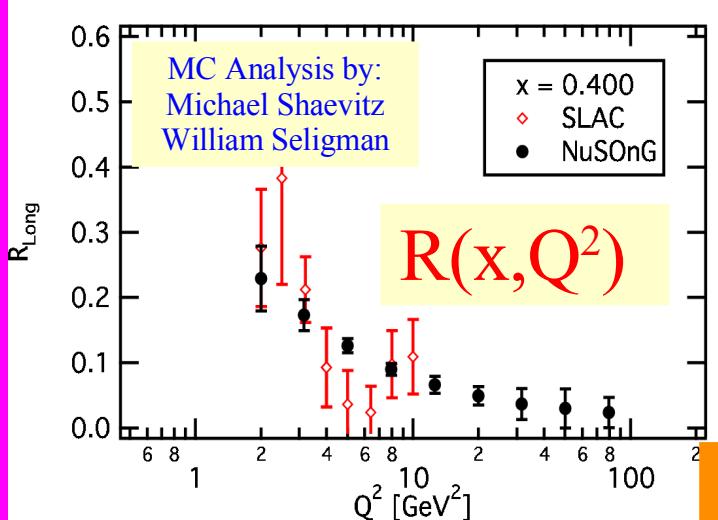
Oooooops!

Use Z to calibrate W



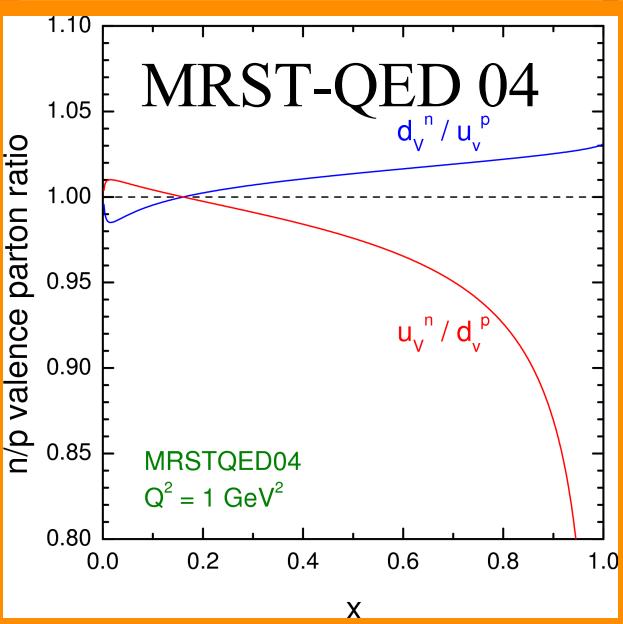
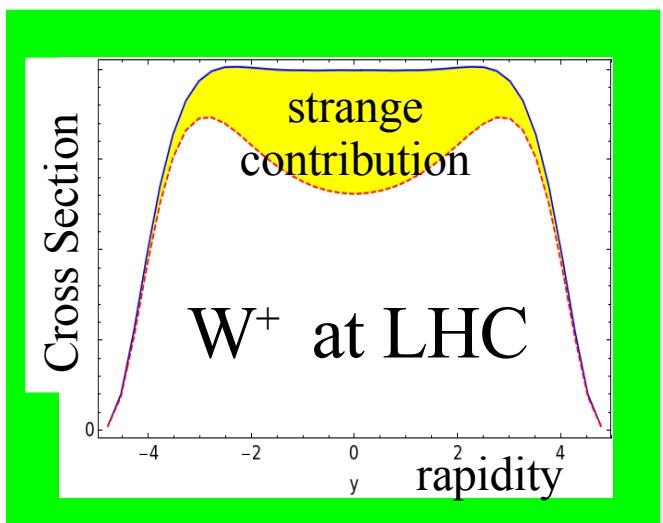
The W-Z correlation is limited by the uncertainty coming from the strange quark distribution

The Puzzles

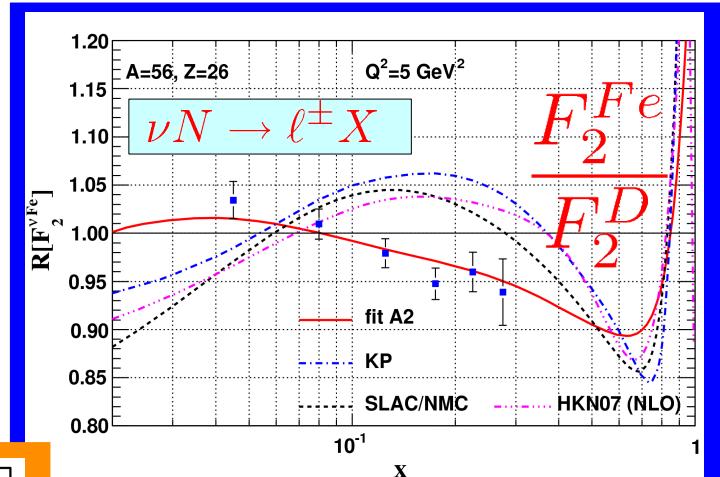


Need independent SF extraction

$s(x)$ uncertainty: implications for LHC

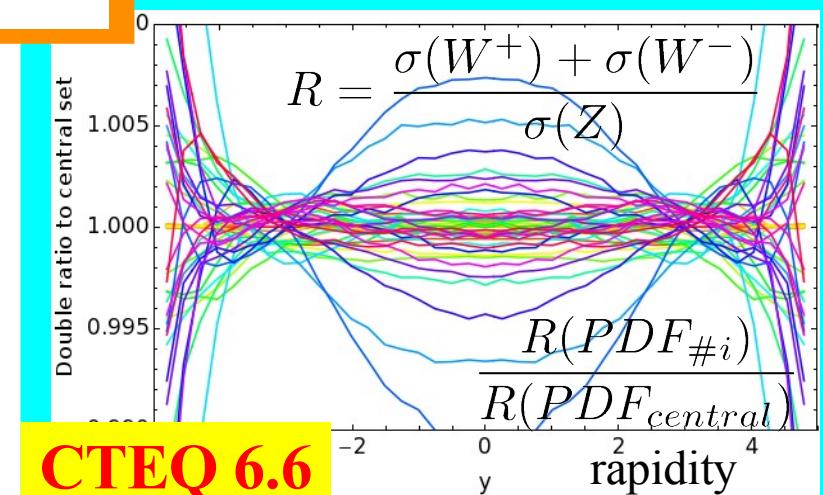


Isospin Violation: cannot ignore



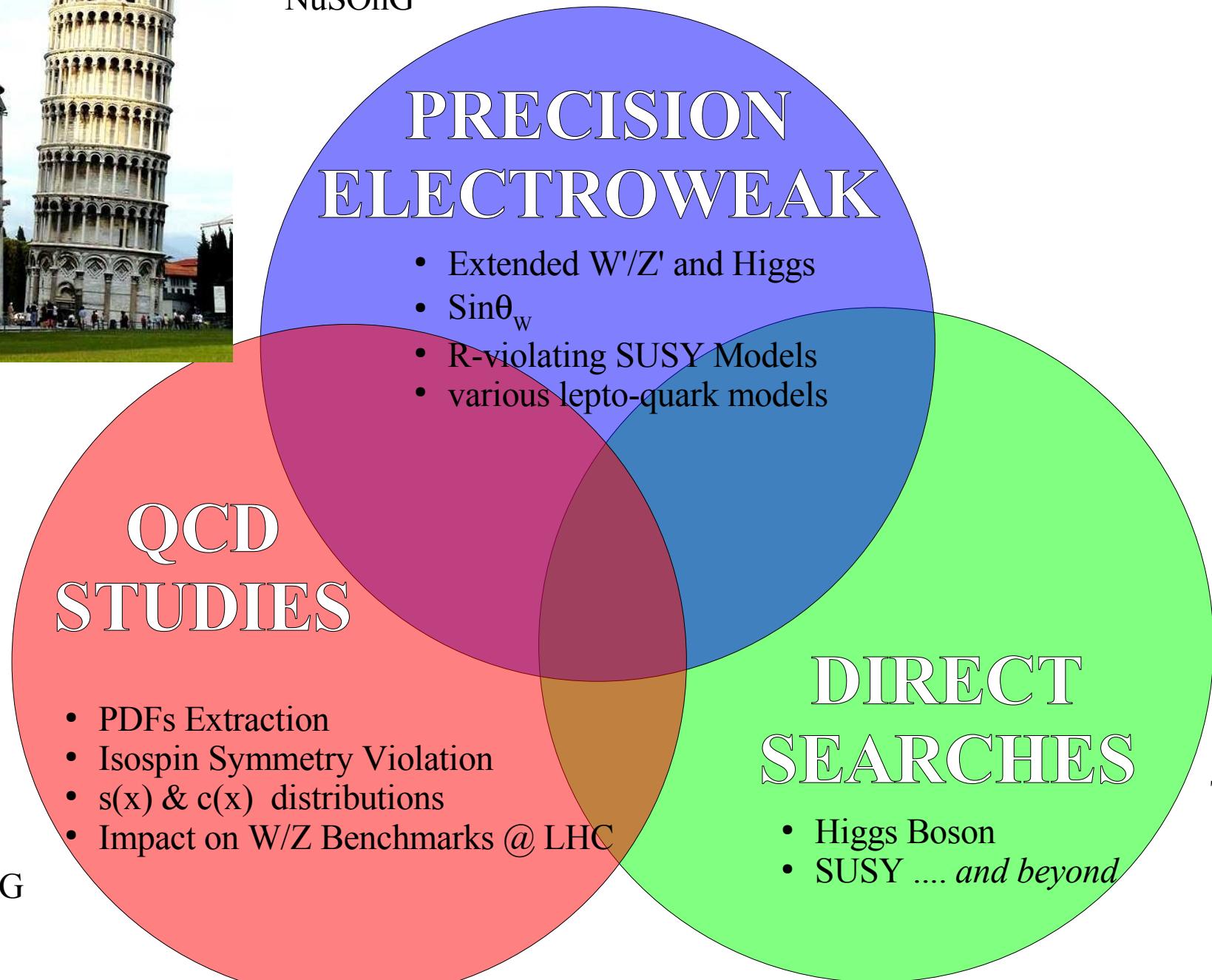
Nuclear Modifications limit CTEQ PDFs

$s(x)$ uncertainty: Challenge for M_W





NuSOnG



NuSOnG

Neutrinos provide a variety of avenues for exploration

Need to address the mysteries of masses and mixings

Precision EW measurements probe the multi-TeV region

Insights into:

Isospin symmetry, $S(x)$, (*and hence $\sin\theta_W$*)

Heavy Quark contributions (*including intrinsic heavy quarks*)

Nuclear corrections are not “**Carved in Stone**”

Present limits on our knowledge of ν has implications for:

PDF extraction

Flavor separation, and heavy flavors

Example: W/Z Benchmarks at LHC

**Neutrinos provide a rich physics program
complementary to the LHC**